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FLOW IN THE TIP GAP OF A RECTILINEAR
TURBINE CASCADE

by

Metin Ilbay Yaras

B. Sci. (Aeronautical Eng.)

A thesis submitted to the Faculty of Graduate
Studies and Research in partial fulfillment
of the requirements for the degree of
Master of Engineering

Faculty of Engineering
Carleton University
Ottawa, Ontario

August 1987

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ABSTRACT

A detailed review of the available literature on the tip clearance effects in turbomachines reveals the lack of understanding of the flow within the tip clearance. Thus, the present experimental study was undertaken to obtain detailed flow field measurements within the tip gap and endwall static pressure measurements in the blade tip region. The observations from these measurements were then examined together with the results of the blade surface pressure measurements so as to obtain the complete picture of the tip leakage flow field.

It was observed that, for clearance sizes seen in practice, the pressure difference driving the tip gap flow is essentially the same as the undisturbed blade surface pressure difference. This is an important result as far as the tip leakage prediction models are concerned. In this connection it was also found that the fluid entering the tip gap is almost exclusively free stream fluid.

Substantial losses were observed within the separation bubble formed at the pressure side corner of the blade tip. The bubble appeared to cover about 30 to 40% of the gap height and its size showed variations with gap height. This accounts for the observed variation of the effective "discharge coefficient" for the clearance passage with changes in the tip clearance.

Based on the detailed experimental results within the tip gap, the leakage models available in the literature were examined.

Some modifications which result in significant simplification and improvements to the predictions are suggested.

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NOMENCLATURE

English Symbols

A	: Area (m^2)
$\bar{A}$	: Aspect ratio of the blade
c	: Nominal blade chord (mm)
C_D	: Discharge coefficient
$C_{D,t}$	: Equivalent drag coefficient for the tip clearance losses
C_f	: Skin friction coefficient
C_L	: Lift coefficient
C_p	: Static pressure coefficient
C_{pt}	: Total pressure loss coefficient
e	: Ratio of tip clearance height to maximum blade thickness at the blade tip
ΔE	: Power loss due to the tip clearance flow (Watt)
h	: Blade height (mm)
H	: Boundary layer shape factor
k	: Contraction factor of the flow through the tip gap
K	: Probe calibration coefficient, further specified by subscripts
K_r	: Retained lift coefficient
$\dot{m}$	: Mass flow rate (kg/sec)
P	: Static pressure (Pa)
q	: Dynamic pressure (Pa)
r	: Annulus radius (mm)

8

r_c : Tip leakage vortex sheet radius (mm)
 Re : Reynolds number
 s : Blade spacing (mm)
 St : Solidity based on tip radius
 t : Tip clearance height (mm)
 t^* : Dimensionless time (defined in eqn. 2.10.12)
 U : Blade speed (m/sec)
 u' : Fluctuating component of axial velocity
at test section inlet (m/sec)
 V : Velocity (m/sec)
 W : Relative velocity (m/sec)
 $\bar{W}$: Height of test section inlet (cm)
 X : See Figure 6.1.1 for definition
 Y : See Figure 6.1.1 for definition
 Z : Spanwise direction
 z_v : Co-ordinate along the vortex sheet starting from the
blade leading edge

Greek Symbols

α_2 : Exit absolute/relative flow angle for vane/blade
 β^* : Stagger angle
 β : Tip gap flow angle relative to the blade chord
 α_m : Mean flow angle: $\arctan \left(\frac{\tan \alpha_1 + \tan \alpha_2}{2} \right)$
 Γ^* : Dimensionless circulation $(2 \cdot \Gamma / V_\infty \cdot C_L \cdot c)$
 T : Blade thickness (mm)
 δ : Maximum thickness to chord ratio at the blade tip

ϕ	: Flow coefficient
ψ	: Work coefficient
ν	: Kinematic viscosity (m^2/sec)
δ	: Boundary layer thickness (mm)
δ^*	: Displacement thickness (mm)
θ	: Momentum thickness (mm)
ρ	: Density (kg/m^3)
η	: Efficiency

Subscripts

bnd	: Endwall boundary layer
CL	: Centerline at test section inlet
e	: Exit
t	: Tip
T	: Tangent to the Blade Pressure Surface
h	: Hub
m	: Mean
N	: Normal to blade meanline
psg	: Passage
R	: Retained
sC1	: End of the settling chamber contraction
SC2	: Beginning of the settling chamber contraction
ω	: Undisturbed value of a particular quantity
o	: Value of a quantity at zero clearance

2D : Two dimensional
1 : Blade row inlet
2 : Blade row exit

1. INTRODUCTION

In the rotating blade row of turbomachine stages, a clearance must be kept between the casing and the blade tip so as to avoid rubbing of the blades against the annulus casing. The presence of this clearance results in substantial changes in the performance due to the following reasons:

- (i) Unloading towards the blade tip;
- (ii) Reduced blade height causing a reduction in the total tangential force acting on the blade;
- (iii) Mixing of the tip gap flow with the main stream resulting in significant total pressure losses.

In addition to these factors, the crossflow associated with the tip clearance flow will lead to off-design inlet flow conditions for the subsequent stage in a multistage machine.

As is seen, the presence of the tip clearance has very significant negative effects. As discussed in Chapter 2, the height of the clearance is one of the most important parameters which determine the magnitude of these effects. Hence, since in turbines the tip clearance size is generally larger than in compressors (due to the fact that the casing expands more than the blades when operating at high temperatures), the tip clearance losses tend to be higher in turbines. During the

operation of the engine, active control of the clearance height is one way of keeping the clearance height, and thus the losses, at low levels. This has been applied to a number of large engines where the additional cost was justified. However, particularly for smaller engines, where, due to the increased relative size of the clearance, the tip losses are even more severe, the application of active clearance control is not feasible. Hence, it is clear that the tip clearance flow has to be understood in detail so as to be able to investigate other approaches for reducing, or at least predicting, the losses associated with the tip clearance flow.

In order to determine the aspects in which a valuable contribution can be made to the investigation of the tip clearance flow, the present study began with a detailed review of the previous tip clearance studies (see Chapter 2). In that chapter both compressor and turbines studies are reviewed since the results of either case appear to be useful for the other. The review shows that the unloading towards the blade tip and the effect of the tip leakage vortex (formed as a result of the interaction of the tip leakage flow with the mainstream) on the flow in the tip region of the blade suction surface are quite well understood. The development of the leakage vortex as it proceeds towards the exit of the blade row has also been investigated. In order to reduce the tip gap effects various casing and blade treatments have been suggested. An extensive

data base of efficiency variation with clearance size for various turbomachines is also available in the literature. Finally, based on the present understanding of the flow and the available experimental data, some models for predicting the blade surface pressure distribution, the tip leakage vortex structure and the losses due to tip clearance have been introduced, which are also included into the review.

From the literature survey, it was apparent that the flow properties within the tip gap have been investigated very little. This is surprising since this type of information should be very useful for further understanding of the sophisticated flow in the blade tip region gap, leading to more effective designs for blade tip and casing treatment and more accurate prediction models. Thus, the present experimental study was aimed towards obtaining a better understanding of the flow within the tip gap.

In the study, a planar cascade of turbine blades was used with the open jet wind tunnel in the Hydraulics Laboratory at Carleton University. The turbine blades were scaled from geometric specifications obtained from Pratt & Whitney Canada and were of 250 mm chord and 202.3 mm span. The Reynolds number based on chord length and test section inlet velocity was kept at 4.3×10^5 (which corresponds to an inlet velocity of about 30 m/sec, i.e., incompressible flow), except for the experiments where Reynolds number effects were investigated. The clearance-

to-chord ratio was varied from 1.9% to 3.2%. A more detailed description of the apparatus is given in Chapter 3.

The blade surface pressure measurements close to the blade tip showed similar trends to the results observed in previous studies. Blade surface pressures were also measured at other spanwise locations covering the complete blade surface up to the midspan. Examination of these results together with detailed endwall static pressure measurements at the blade tip region yields interesting conclusions about the pressure difference driving the tip clearance flow (Chapter 5). Detailed three-hole probe measurements were performed within the tip gap, giving the tip clearance velocity, flow angle and total pressure distribution (Chapter 6). The examination of these results, together with the endwall and blade static pressures, leads to a much improved understanding of the flow within the gap. Using the results of the three-hole probe measurements, the mass flow rate through the tip clearance is calculated and the variation of its magnitude with clearance size is examined.

Finally, based on the better understanding of the tip gap flow achieved from the observations made in the present study, the leakage models available in the literature are examined and an improved model is suggested.

2. REVIEW OF PREVIOUS WORK

The design of turbomachines with high efficiency has always received considerable attention. Important gains in the efficiency can be obtained by reducing the aerodynamic losses. Therefore, a significant amount of work has been done on the understanding and prediction of these losses.

Since the secondary losses account for a substantial portion of the total losses, priority was given to this area. Owing to the fact that the investigation of the tip leakage flow requires a good understanding of secondary flows, it was not until the early 1950's that detailed studies on tip clearance flow started. Depending on the clearance size compared to the annulus height, the magnitude of the clearance losses relative to the total aerodynamic losses can vary over a wide range. For example, according to Peacock (1982), Osborne Reynolds, who held the first patent on a turbomachine, did not continue to work on a small water turbine that he designed after realizing the inefficiency of the machine. This was presumably caused by the tip clearance losses whose relative magnitude was quite significant due to the small size of the engine.

Today, there is a tendency to increase the pressure ratio of the compressors and turbines so as to increase the engine performance. This results in very small annulus heights at the

last stages of compressors and at the first stages of turbines, which implies substantially larger tip clearances relative to the blade height. Therefore, the aerodynamic losses associated with the tip clearance flow are even more significant in recent engines than they were a few decades ago.

2.1 Configurations Used For Tip Clearance Flow Studies

The tip clearance flow is very complicated and there is a large number of parameters affecting the flow. Therefore, different configurations have been used for tip clearance flow studies so as to investigate various effects separately. The configurations that have been used are introduced in the following paragraphs in order of increasing accuracy in simulating the real flow.

The simplest configuration is an isolated airfoil mounted between plane walls, with a tip clearance at one end of the airfoil. Sugiyama (1971) and Lewis & Yeung (1977) used this type of a configuration. In some cases, instead of simulating the tip clearance at one end of the airfoil, the airfoil is split at midspan so as to simulate the tip clearance flow without the effect of endwall boundary layers. Note that due to the symmetry, using the method of images, the flow in a desired tip clearance height can be investigated with a split height twice that of the clearance height. The work of Lakshminarayana & Horlock (1962), done with this type of configuration, was an

important step in the understanding of the tip clearance flow. Finally, it is also possible to simulate the relative endwall motion while still using an isolated aerofoil. Gearhart (1966), who investigated the cavitation problem associated with the tip leakage flow, performed experiments using a single blade where the relative blade motion was simulated with a moving belt.

A rectilinear cascade is probably the most widely used configuration for tip clearance studies. In some of these studies the endwall motion was not introduced and the tip clearance was simulated with a gap between the blades and one of the endwalls (eg. Sjolander & Amrud (1985), Rehbach (1960)). In some other cases the tip clearance is simulated with blades split at midspan so as to dispense the endwall boundary layer effect (see discussion in the previous paragraph). For example, Lakshminarayana & Horlock (1965), Khabbaz & Senoo (1961), Yokoyama (1961) used this configuration. The next step was the introduction of the endwall motion to rectilinear cascades using moving belts (Dean (1954), Graham (1986)).

The configuration that is closest to the real case is undoubtedly rotating machinery. However, because of the difficulties encountered in taking measurements within a rotating blade row, information on tip clearance effects from this type of test section has mainly been obtained from measurements at inlet and at exit of the blade row. This information has been

obtained either directly in the form of engine performance (eg. Kofskey & Nusbaum (1967), Szanca et al. (1974), Kofskey (1961)) or from the detailed distribution of various quantities at the exit blade (eg. Hutton (1955), Haas & Kofskey (1977), Inoue et al. (1986)).

2.2 Flow In Rotor Blade Passages

In this section the passage flow picture, in the absence of the tip clearance, is briefly presented so that the detailed discussions on the tip clearance flow given in the remainder of the chapter can be followed more easily.

From the secondary flow studies it is known that the endwall boundary layer rolls up into a vortex inside the passage (passage vortex) which, due to the pressure gradient in the passage, is located at the blade suction surface-endwall corner. Furthermore, due to the interaction of the endwall boundary layer flow with the blade leading edge, a horseshoe vortex is formed. The pressure side leg of this horseshoe vortex rotates in the same direction as the passage vortex, and Langston et al. (1977) proposed that this leg merges with the passage vortex. This was also observed in the flow visualization studies of Sieverding & Bosche (1983). The rotation of the suction side leg of the horseshoe vortex is the opposite of the passage vortex and Klein (1966) stated that it is wrapped around the passage vortex while

Sjolander (1975) and Langston et al. (1977) suggested that it is located at the corner of the endwall and blade suction surface, i.e., underneath the passage vortex. The flow visualization studies by Sieverding & Bosche (1983) support Klein's (1966) model. In the light of these observations, the passage flow in the case of zero tip clearance can be presented schematically as shown in Fig. 2.2.1.

In stationary blade rows, the above flow picture is seen both at the hub and at the tip. However, in unshrouded rotating blade rows, while the flow in the inner part of the passage is still as discussed in the previous paragraph, in the outer part, the flow picture is substantially different due to the tip clearance. The remainder of this chapter includes a detailed review of the studies which have improved the understanding of the flow in this region.

2.3 Tip Clearance Flow In Compressors and Turbines

Reduced blade height, blade unloading towards the tip, and mixing of the tip gap flow with the mainstream resulting in considerable total pressure losses are the significant negative effects of tip clearance which cause substantial reduction in the performance of the machine. In compressors, as a result of the decelerating flow through the blade passages, the tip clearance flow may have an even more significant effect on the aerodynamic

Fig. 2.2.1 Endwall Flow Models By Klein (1966) And
Langston et al. (1977)
(reproduced from Sieverding (1985))

losses and it can also affect the stability of the machine. This is probably the reason that the most extensive tip leakage studies have been made in compressors.

There are a number of factors to be considered when applying the observations obtained from tip clearance studies in decelerating flows to accelerating flows and vice versa. One of them is the fact that the endwall boundary layer will behave differently under accelerating and decelerating free stream conditions. Furthermore, on compressor blades the maximum load is generally concentrated at the leading edge while on turbine blade blades, loading tends to be distributed more or less uniformly over the blade length. One more difference, which, as far as the tip leakage flow is concerned, is probably the most significant one, is the relative endwall motion. In compressors and turbines this motion is in opposite directions and therefore, their effect on the leakage flow will be different (Fig. 2.3.1). Nevertheless, tip clearance effects observed from accelerating flow stages can still provide insights into the clearance effects in decelerating flow stages and vice versa. In order to confirm this statement, Yokoyama (1961) performed tip clearance experiments with a stationary endwall in two different cascades, one of compressor blades and one of turbine blades. The blade angles were set such that:

$$\alpha_1(\text{comp.}) = \alpha_2(\text{turbine}) ; \alpha_2(\text{comp.}) = \alpha_1(\text{turbine}) \quad (2.3.1)$$

(a)

(b)

Fig. 2.3.1 Endwall Motion Effect On The Tip Clearance
Flow a) Turbine b) Compressor

The reason for this angle setting can clearly be seen in Fig.

2.3.2. In each cascade a number of blades close to the centre were split at midspan so as to investigate the tip clearance effect without endwall boundary layer effects. The blade surface pressure distributions and spanwise lift coefficient distributions showed very similar trends for both cascades, confirming the similarity between tip clearance effects on passage flows in compressor and turbines in the case of no endwall motion.

2.4 Tip Clearance Studies Using Isolated Blades and Rectilinear Cascades With No Endwall Motion

2.4.1 The Effect of the Tip Leakage Vortex On the Blade Suction Surface Pressure Distribution

The first extensive study with a rectilinear cascade appears to have been performed by a number of graduate students in the M.I.T. Gas Turbine Laboratory in 1953-1954. Using this accumulated data, Dean (1954) presented a detailed picture of the flow at a compressor blade tip. In the experiments, clearance sizes up to 10% of chord length were investigated and with increasing clearance size a continuous increase in the magnitude of the suction peak near the blade tip (caused by the tip leakage vortex) was observed. Furthermore, the experimental results

Fig 2.3.2 Velocity Triangles In A
a) Turbine Stage b) Compressor Stage
(reproduced from Moustapha (1986))

indicated a continuous rearward shift of this peak with increasing clearance size. The same trend in the peak location has subsequently been observed by Khabbaz & Senoo (1961) in a compressor cascade where the endwall boundary layer effect was avoided by using a midspan gap, by Lakshminarayana & Horlock (1962) with a single airfoil split at midspan and by Sjolander & Amrud (1985) in a turbine cascade with tip clearance at one end of the blades.

In agreement with Dean's (1954) result, Sjolander & Amrud (1985) observed an increase in the suction peak near the blade tip with increasing clearance size. This was also seen by Lakshminarayana & Horlock (1962) using a single airfoil split at midspan. The enhancement of the suction peak is clearly an indication of the strength of the tip leakage vortex. For very large clearances one would expect this peak to reduce, since the finite wing situation is approached. This is in fact seen in the results of Lakshminarayana & Horlock (1962).

From some of the cascade tests the presence of multiple vortices at the blade tip can clearly be seen from the presence of multiple peaks in the blade surface static pressure distribution near the blade tip: for example the work of Khabbaz & Senoo (1961) where a compressor cascade accommodating blades split at midspan was used and the turbine cascade study of Sjolander & Amrud. In the latter work, the presence of these

multiple vortices was commented on by the authors.

2.4.2 Spanwise Distribution of the Blade Lift Coefficient

Sugiyama (1975) used an isolated wing in a rectangular test section to determine the endwall boundary layer effect on spanwise lift and drag distribution on a wing with tip clearance. The suction side pressure distribution close to the wing tip indicated considerable variation with changes in the endwall boundary layer displacement thickness while the effect on the pressure surface was negligible. Even though as the endwall boundary layer thickness is increased, the chordwise distribution of the suction surface pressure near the blade tip does not vary in a certain trend, the resultant effect is a considerable reduction in the local lift. This phenomenon has already been observed from secondary flow studies with no tip clearance. From Sugiyama's results it is also seen that the presence of the tip clearance increases the spanwise blade portion over which the lift distribution is affected by the variations in the endwall boundary layer parameters. In the case of nonzero clearance, very close to the blade tip the lift rises rapidly before finally dropping as the tip is approached. More detailed discussion on this point is given in the later part of this section. Sugiyama makes use of the concept of retained lift at the wing tip, first introduced by Lakshminarayana & Horlock, (1962) (see section 2.10). This is a hypothetical lift obtained graphically by

neglecting the additional increase in the lift due to the clearance flow very close to the tip and extending the spanwise lift coefficient distribution curve to the wing tip (Fig. 2.4.2.1). The author states that the parameter formed as $(C_{L\infty} - C_L)/(C_{L\infty} - C_L(\text{tip}))$, where $C_{L\infty}$ is the lift under uniform, two dimensional flow conditions and $C_L(\text{tip})$ is the retained lift at the blade tip, does not vary with the angle of attack and endwall boundary layer displacement thickness and appears to be a function of the tip clearance height only.

The work of Khabbaz (1959) (the paper published by Khabbaz & Senoo in 1961 was based on the work presented in this technical laboratory report), where the tip clearance effect is investigated using the mirror image technique, indicated that the loading slightly increases towards the blade tip. This has been observed by all investigators who obtained spanwise lift distributions from their experiments with nonzero tip clearance (eg. Lakshminarayana & Horlock (1962), Sugiyama (1975) and Sjolander & Amrud (1985)), (see Fig. 2.4.2.1). Khabbaz (1959) explains this increase in the loading at the blade tip using a momentum flux theory (see Fig. 2.4.2.2). Since in compressors the pressure at the blade outlet (p_2) is higher than at the inlet (p_1), considering the control volume in Fig. 2.4.2.2, the momentum flux into the volume is larger than the momentum flux leaving the volume. Khabbaz noted that this implies that some of the air must leave the cascade by passing through the passage so

Fig. 2.4.2.1 Spanwise Lift Distribution At Various Gap-to-Chord Ratios (reproduced from Lakshminarayana & Horlock (1962))

Fig. 2.4.2.2 Momentum Flux Theory Suggested By Khabbaz (1959)

as to satisfy continuity. He states that presumably this additional fluid is passing through the blade row near the blade tip, increasing the loading in that region. Using the same argument, he also notes that in the case of a turbine the loading at the tip should decrease with increasing clearance. However, from the turbine cascade experiments of Yokoyama (1961) and Sjolander & Amrud (1985), it is clear that the loading near the blade tip increases as the clearance size is increased. This clearly undermines Khabbaz's argument. Furthermore, Yokoyama (1961), from his compressor cascade experiments (using blades split at midspan) observed that the flow angle and axial velocity at the blade row exit is reduced towards the blade tip, and Sjolander & Amrud (1985) from their turbine cascade experiments found that the increase in the loading towards the blade tip is in the axial component rather than in the tangential component. This again shows that the real flow picture at the blade tip cannot be explained with Khabbaz's (1959) argument. The increase in the loading very close to the blade tip is simply explained by the presence of the tip leakage vortex on the suction side, which is consistent with both Yokoyama's (1961) and Sjolander & Amrud's (1985) observations.

As the clearance is increased, the blade will approach the finite wing situation. In this case the blade is expected to unload towards the blade tip. Lakshminarayana & Horlock's (1962) and Sugiyama's (1970) results clearly indicate this unloading

with increasing tip clearance. However, as seen from Fig. 2.4.2.1, for the clearance sizes seen in practice (i.e., up to about 4% of the blade height) this unloading is quite small. From this figure it is also seen that even at very large clearances the increased loading at the blade tip due to the tip leakage vortex is still present; its magnitude is, however, substantially reduced, indicating that the classical wing tip vortex situation is approached.

2.5 Simulation of the Relative Blade Motion Using Moving Belts

In the above discussed configurations the pressure difference across the gap is the dominant factor determining the tip leakage flow. However, when endwall motion is taken into account, the viscous drag of the wall also appears to be an important factor affecting the flow through the clearance (see Fig. 2.3.1). Dean (1954) appears to have been the first to investigate endwall motion using a rectilinear compressor cascade with a moving endwall. His belt covered a region from 0.4 chord length upstream of the leading edge to the cascade exit. From his experiments he concludes that for the case of a compressor the endwall motion shifts the leakage vortex core towards the pressure side of the passage since the endwall motion increases the mass flow rate through the gap (viscous drag effect). However, he notes that this shift does not continue above a certain wall speed and the vortex remains at the same place.

Peacock (1982) notes that this observation appears to contradict the results of Gearhart (1966) who performed experiments with a moving endwall and a single blade. Gearhart's results show that the mass flow rate through the gap increases with a rising rate as the endwall speed is increased. However, it should be noted that Dean's experiment includes the effect of the passage vortex (secondary flow) which was absent in Gearhart's experimental set up. This, as discussed in the next paragraph, probably explains the contradiction.

As was noted in section 2.2, in the absence of the tip clearance, the passage vortex is located at the blade suction surface-endwall corner. When the clearance is opened, due to the formation of the tip clearance vortex, this passage vortex is shifted towards the pressure side of the passage. Allen & Kofskey's (1955) visualization studies at the tip region of a turbine rotor clearly shows this interaction. Undoubtedly, the passage vortex will be a factor that prevents the tip leakage vortex from moving too far away from the suction surface. In fact, Lakshminarayana & Horlock's (1965) vorticity measurements at the exit of a compressor cascade indicate that the secondary flow causes the leakage vortex to be located nearer to the suction surface than observed when there was no endwall in the tip gap. This probably explains the behaviour observed by Gearhart.

Gearhart's (1966) study was mainly aimed towards reducing the cavitation problem in hydraulic turbomachine rotors. He distinguishes between two types of cavitation. One of them occurs in the separation bubble at the pressure side corner of the blade tip while the other one is related to the tip leakage vortex (note that cavitation bubbles are a good way of visualizing the tip leakage vortex which was in fact used by Rains (1954)). In order to avoid the formation of a separation bubble on the blade tip he suggests rounding the pressure surface corner. For reducing the strength of the tip leakage vortex, which in turn will reduce the amount of cavitation in that vortex, he suggests a tip clearance gap which is slightly divergent. It should be noted that, while reducing the gap cavitation effect, the former geometric modification (i.e., rounding the corner) will cause a considerable increase in the tip clearance mass flow rate. However, the fact that whether this is undesirable or not is not entirely clear: it might be better to have somewhat increased mass flow rate through the tip gap if this fluid can be made to have a much lower total pressure loss; this point certainly needs more investigation. One more point worth mentioning is that according to Gearhart the experiments performed by Shalnev (1958) indicated that the separation bubble size does not change with Reynolds number. However, this is not the case with the results of our experiments (see Chapter 8).

Using a turbine cascade, Klein (1966) examined the effect of tip leakage and endwall motion on the low energy fluid region at the blade suction surface-endwall corner of the passage. He observed that when the clearance size is opened, the low energy fluid region (passage vortex) shifts towards the pressure side of the passage and the losses associated with this secondary flow are substantially reduced. The losses near the wall are further reduced with endwall motion which is due to the reenergizing effect of the endwall motion (viscous drag effect).

Rehbach (1960) appears to be another experimentalist who has taken the relative endwall motion into account in his tip leakage flow studies. The experimental configuration differs slightly from the above quoted ones in that it was an annular cascade in which the casing moved and the blades were stationary. With this test rig he performed both stationary and moving endwall tests and compared the results to the ones that he had obtained from a rectilinear cascade with no endwall motion. He concluded that for turbine stages with practical clearance sizes, the effect of relative endwall motion at practical speeds on the tip clearance losses is very small. This implies that, for turbines the results of studies on tip clearance losses performed with stationary endwall are going to closely resemble the tip clearance losses seen in the actual turbomachine. This result was found to be valid also for compressors by Hubert (1960) who investigated the effect of the endwall motion in a

compressor stator.

The most recent work with this type of configuration is that by Graham (1986), who performed experiments using high pressure axial turbine blades in a water analogy rig. This study is mainly oriented to the effects of tip clearance size and relative blade motion on blade unloading. He notes that, as a result of a weaker tip leakage vortex, the unloading at the blade tip is increased with endwall motion. At the engine equivalent endwall speed this increase in unloading is not very large; however, it appears to be very large for twice the engine equivalent endwall speed. As expected, the experiments at different clearance sizes indicated a reduction in the clearance flow with decreasing clearance size. On the other hand, it is noted that, regardless of the belt speed, the reduction of the leakage is nonlinear. Based on the experiments reported in this study, this can be attributed to the fact that the separation bubble size relative to the clearance height varies for different clearance sizes. As the belt speed was increased, a decrease in the leakage flow was observed, which is simply a result of the viscous drag effect. When the endwall motion is introduced, the local increase in the loading at the blade tip appeared to be reduced which is clearly an indication of decreased vortex strength.

Finally, although it was done with no endwall motion, the work

of Bindon (1986) using a rectilinear turbine cascade is worth mentioning in this section. As was noted above, Gearhart suggested rounding the pressure surface corner of the blade tip in order to avoid the formation of the separation bubble and, therefore, the cavitation associated with it. In turbomachines with air as the working fluid the existence of the separation bubble has been recognized for some time, but surprisingly has received very little attention. Bindon (1986), is probably the first to investigate this phenomenon in detail. From his measurements he observed very high velocities at the pressure side corner of the blade tip. The author notes that this explains the burnout problem at the blade tip pressure surface corner seen in some existing turbines. Even though rounding the pressure surface corner may solve this problem, the author suggests the alternative of blanketing the corner with a cooling air film discharged radially near the tip of the pressure surface. The latter may be a better solution since it will not increase the tip clearance mass flow rate, as would be the case with the rounded corner, and may even decrease it by partly blocking the gap flow.

2.6 Rotating Turbomachinery

When the relative motion of the blades is considered, in addition to the leakage vortex and passage vortex, a so called scraping vortex is formed (presumably this name is used because

the vortex is formed by the scraping effect of the blade on the endwall boundary layer). Allen & Kofskey (1955), from their smoke flow visualization studies in a low speed turbine, clearly observed the presence of this vortex. They also noted that even when the blade tip is out of the endwall boundary layer region, the endwall boundary layer is rolled into a scraping vortex. Undoubtedly, in this case, the scraping vortex is a result of the motion of the pressure field rather than the physical presence of the blade itself. Phillips & Head (1980) also noted the presence of the scraping vortex from their visualization studies in an axial-flow compressor. It is important to note that in the case of a compressor the scraping vortex is on the pressure side of the blade and rotates in the same direction as the leakage vortex while in turbines it forms on the same side as the leakage vortex with a rotational direction opposite to the leakage vortex.

The information obtained within the blade row has been limited to flow visualization experiments since taking quantitative measurements within a rotating blade row is quite difficult. Therefore, for rotating machinery the quantitative information on tip leakage effects has been obtained mainly from the overall performance variation and from radial surveys at the rotor exit. Studies of this type are reviewed in the following sections.

2.6.1 Effect of Tip Clearance On Performance

Data obtained from various radial and axial impellers indicate a roughly linear decrease in efficiency with increasing clearance size, as seen in Figures 2.6.1.1 and 2.6.1.2. These impeller data were summarized by Senoo & Ishida (1986) who derived a loss correlation for centrifugal and axial impellers. A similar linear variation is also seen in Fig. 2.6.1.3 which includes mixed flow and axial flow turbomachines, compiled by Hesselgreaves (1969), for the purposes of checking the accuracy of his loss correlation (for the notation used on the horizontal axis of the graph, refer to eqn. 2.10.2.2). However, as seen from Figures 2.6.1.1 to 2.6.1.3, the data are not simply scattered but there are systematic differences between the results obtained from different machines at the same relative clearance. This implies that the tip clearance size is not the only factor affecting the tip clearance losses. One of these factors appears to be the degree of reaction at the blade tip, as discussed in detail in the following paragraph.

Kofskey & Nusbaum (1967) investigated the tip clearance effect on a two-stage turbine designed with 0.862 tip reaction. The results indicated a 3.7 per cent efficiency decrease for every 1% increase of the tip clearance to annulus height ratio. Furthermore; Szanca et al. (1974), who investigated the tip clearance effect on a research turbine with 0.805 tip reaction,

Fig. 2.6.1.1 Efficiency Variation With Tip Clearance, Centrifugal Impellers (reproduced from Senoo & Ishida (1986))

Fig. 2.6.1.2 Efficiency Variation With Tip Clearance, Axial Impellers (reproduced from Senoo & Ishida (1986))

Fig. 2.6.1.3 Tip Clearance Loss Correlation Suggested By Hesselgreaves (1969)

quoted an efficiency reduction of 1.9 points for every 1% increase in the tip clearance. If these two results are compared to the 1.75 points efficiency drop for every 1% tip clearance increase obtained by Kofskey (1961) from an impulse design turbine stage, it is seen that increasing reaction at the blade tip increases the rate of efficiency reduction with increasing tip clearance. This is caused by the effect on the mass flow rate through the tip clearance of increasing the relative velocity through the rotor: high reaction at the blade tip results in a large pressure difference across the tip gap, thus causes higher kinetic energy associated with the tip leakage flow normal to the blade chord.

2.6.2 Effect of Tip Clearance On Rotor Exit Conditions

Hutton (1955), from his measurements downstream of a single stage axial compressor impeller, noted that when the tip clearance size is increased, the pressure rise all along the blade is reduced, with the maximum drop being close to the tip region. He also investigated the variation of the axial velocity with tip clearance and concluded that increasing the clearance size reduces the axial velocity close to the tip, which was also seen by Yokoyama (1961) in his cascade tests. Furthermore, Hutton (1955) observed a significant increase in the axial velocity close to hub. This clearly shows that the region in which the flow conditions are affected by the tip clearance

extend over a substantial portion of the annulus area. Patel (1980) performed pressure and temperature measurements downstream of an axial gas generator turbine so as to determine the tip clearance effect on the local efficiency at various spanwise locations. As is seen in Fig. 2.6.2.1, the radial variation of efficiency changes very significantly as the clearance size is increased, although the efficiency penalty is seen mainly between midspan and the casing.

Furthermore, from measurements at the exit of a two stage turbine, very close to the outer wall Kofskey & Nusbaum (1967) observed a slight increase in total pressure with increasing clearance size. This is explained by the substantial underturning seen in this region: for large clearances the fluid close to the endwall passes through the stage with relatively small turning. Therefore, this fluid contributes little to the stage work output and retains much of its energy. The underturning was also observed by Davino & Lakshminarayana (1982), Szanca et al. (1974) and Haas & Kofskey (1977). The last two references also indicate that the largest changes occurred in the blade region between the midspan and the tip section.

The studies of Inoue & Kuroamaru (1984) and Inoue et al. (1986) are noteworthy since very detailed vorticity measurements were performed at the exit of the rotor. This provides detailed

Fig. 2.6.2.1 Effect Of Tip Clearance On The Radial Distribution Of Efficiency
(reproduced from Patel (1980))

information about the relative sizes of the various vortex structures.

The study of Inoue & Kuroumaru (1984) was done at the exit of an axial fan. The radial velocity distribution near the hub clearly shows the trailing vortex, while near the tip the leakage vortex is observed. The radial velocity distribution near the tip also indicates another relatively small vortex structure with the same rotational direction as the leakage vortex; this is the so called scraping vortex. Note that even though they appear to be located very close to each other, since the considered turbomachine is a fan, the scraping vortex is formed on the pressure side of the blade while the tip leakage vortex is on the suction side of the blade. The authors also note that the downstream measurements indicated higher turbulence quantities in the leakage vortex which they explain by the fact that turbulence energy is generated by the mean vortex motion.

The measurements by Inoue et al. (1986) at the exit of an axial compressor gave very interesting results regarding the location and the size of the tip leakage vortex. For the clearance sizes examined (up to 5% of the blade tip chord), with increasing clearance the vortex moves towards the pressure side of the adjacent blade. This apparently contradicts the result of Lakshminarayana & Horlock (1962), who performed experiments on an isolated airfoil split at midspan. Lakshminarayana & Horlock's

Downstream vorticity measurements indicated that for very small clearances the vortex is far from the blade suction surface, and it moves towards the surface as the clearance size is increased. They explain this result as follows :

" For the same pressure difference the leakage velocity is greater for small gap to chord ratio than large gap to chord ratio. The resultant velocity in the gap is the vector sum of the leakage velocity and the mainstream velocity in the gap. Hence for small values of gap to chord ratio the resultant velocity is inclined at a large angle to the streamwise direction. As the magnitude of this resultant velocity is large for small gap-to-chord ratio, the leakage flow reaches further into the mainstream flow."

It is worth mentioning that the measurements obtained in the present study do not support the picture presented by Lakshminarayana & Horlock (1962). It was found that the pressure difference driving the flow through the gap remains essentially the same for a practical range of clearances and, as one might expect, the velocities in the gap are likewise very similar. This implies that when the clearance size is increased within practical limits, the total momentum of the leakage flow normal to the passage flow direction will increase. Therefore, when the clearance size is increased, the leakage vortex should form further away from the suction surface of the blade which

supports the results observed by Inoue et al. (1986).

For clearances substantially larger than those seen in practice, the pressure difference will of course drop towards the endwall. This means that the leakage velocity in the outer region of the clearance will be smaller than the leakage velocity seen in a small clearance with the same blade tip pressure difference. In this case the tip leakage vortex may start to move towards the suction surface as the clearance is increased. However, this still does not help to explain Lakshminarayana & Horlock's results since their data shows this trend for both very small and very large clearances.

2.7 Optimum Clearance Size

At a certain clearance size the tip vortex strength will just be enough to remove the low energy fluid from the endwall - suction surface corner and the passage and tip vortex strengths will be equal. It has been suggested that this clearance size represents an optimum clearance and that it depends on parameters such as tip leakage vortex strength and endwall boundary layer thickness (which will determine the strength of the passage vortex and the scraping vortex). Whether it is an accelerating or decelerating flow stage is also important, since it effects the direction of rotation of the scraping vortex and its location relative to the blade. The latter is significant as far as the

interaction between the tip leakage vortex and the scraping vortex is concerned. Furthermore, for small clearances, besides the passage vortex, the vorticity associated with the horseshoe vortex also has to be considered in the determination of the optimum clearance size : the existence of the horseshoe vortex for clearances smaller than 1% was observed by Amrud (1985) and Bindon (1987). The presence of an optimum clearance is important because it shows that the smallest possible clearance is not always desirable. The first experimental data where the optimum clearance is observed is the data of Dean (1954) (Fig. 2.7.1). Hubert's (1960) data also confirms the existence of an optimum clearance (Fig. 2.7.1). Finally, from their compressor cascade experiments with strong secondary flow, Lakshminarayana & Horlock (1965) concluded that the optimum clearance size is 4% of chord length. Lakshminarayana (1970), based on his modeling of the passage flow in the blade tip region, gives an equation for determining the optimum clearance size based on the sum of the circulations associated with the tip leakage, passage and scraping vortices being equal to zero.

There is also some evidence of an optimum clearance in rotating machinery experiments. Hutton (1955), from his experiments with an axial-flow impeller, quotes an optimum clearance of 2% of the blade height for which the efficiency reaches its peak value.

Even though the above discussion indicates the possible

Fig. 2.7.1 Variation Of Loss Coefficient With Tip Clearance (reproduced from Lakshminarayana & Horlock (1962))

existence of an optimum clearance, Senoo & Ishida (1986) presented the data obtained from seven different axial impellers (Fig. 2.6.1.2) which shows that for practical clearance sizes the efficiency continuously improve as the clearance size is decreased. This implies that even though for some configurations an optimum clearance may exist, in order to draw more general conclusions, more research has to be done on the parameters that effect the optimum clearance size.

2.8 Tip Clearance Effect On Compressor Stall

As was indicated at the beginning of this chapter, the tip clearance flow in compressor stages is particularly important due to its influence on surge and stall. Therefore, a short review of the studies on the tip clearance effect on compressor stall is included.

McNair (1958) attempted to draw some general conclusions on the tip clearance effects on stalling pressure rise, using the available data in the literature. However, he found a large variation in the sensitivity of various compressors to tip clearance (Fig. 2.8.1). He attempted to correlate the pressure rise variation with a number of parameters, and eventually concluded that if the slopes of the curves in Fig. 2.8.1 (which appear to be nearly linear within the clearance range examined) are plotted against $S_t/(V_z/U_t)$ where S_t is the solidity at the

Fig. 2.8.1 Peak Pressure Rise vs. Clearance Area/Annulus Area (reproduced from McNair (1960))

Fig. 2.8.2 Correlation Suggested By McNair
(reproduced from McNair (1960))

tip, V_z the average axial velocity and U_t the blade tip speed, a fairly good correlation is obtained (Fig. 2.8.2). However, this correlation should be used with caution since it is not supported by physical reasoning.

Khabbaz & Senoo (1961), from their experiments in a rectilinear cascade with a midspan gap, found that the presence of tip clearance is not harmful but in fact shifts the stalling at the blade tip to slightly higher angles of attack. This is presumably due to the fact that the tip leakage vortex energizes the suction surface boundary layer fluid close to the blade tip, thus delaying the separation. However, in the real case where the effects of endwall boundary layer and relative endwall motion are present, this will not be the case. As observed from Dean's (1954) results, obtained in a rectilinear cascade with endwall motion, and from the rotor exit measurements in an axial-flow compressor by Inoue et al. (1986), due to the viscous drag effect the endwall motion moves the tip leakage vortex away from the suction surface. As a result, the stall angle of attack at the blade tip will no longer be improved by the reenergizing effect of the tip vortex. Furthermore, in rotating machinery the oncoming endwall boundary layer will frequently be skewed, which will increase the angle of attack of the blade near the tip. This, of course, will cause the blade to stall first in the tip region.

One of the early studies in this field was performed by Hutton (1955) who investigated the tip clearance effect on an axial-flow impeller. The author states that the stall starts first at the tip, which is explained by the argument given in the previous paragraph. His results indicate that at small clearances the stall is sudden while at larger clearances it occurs more gradually and, interestingly, at relatively larger flow coefficients (Fig. 2.8.3). However, as Jefferson & Turner (1953) point out, the occurrence of stall at higher flow coefficients as the clearance size is increased, appears to be the case for single stage compressors; for multistage compressors a reverse trend is seen. Hutton also noted that the hysteresis observed at small clearances disappears when the clearance size is increased (Hysteresis : the case where the blade would not unstall until a higher flow rate than that at which it had originally stalled). Huppert & Benser (1953) noted that hysteresis is seen in the case of rotating stall (i.e., a substantial portion of the blade span stalls simultaneously and is accompanied by a sharp drop in pressure ratio). Thus, it can be concluded that as the clearance size is increased the blade tip section stalls prior to the other sections of the blade, resulting in a progressive stall with gradual drop in the pressure ratio instead of rotating stall. This is explained by the fact that when the clearance is increased, the work done on the endwall boundary layer by the blades decreases in which case the adverse pressure gradient effect becomes dominant. The fact that at larger clearances the

o Speed 2,000 r.p.m. + Unthrottling

Fig. 2.8.3 Effect Of Tip Clearance On Stalling And Wall Pressure Rise (reproduced from Hutton (1955))

tip section stalls before the other sections implies a reduction in stall margin. This has been observed by a number of investigators. Phillips & Head (1980) performed flow visualization experiments in the tip region of a rotating blade row so as to understand the endwall boundary layer behaviour through the blade row. Their experiments showed that increasing the tip clearance causes stalling at a lighter blade loading. The same result was also obtained by Bettner & Elrod (1983) who, from their experiments in a highly loaded single stage compressor, concluded that a 12.5% decrease in the stall margin occurred when the tip clearance-to-span ratio was doubled. Furthermore, Moore & Osborn (1977) observed a similar trend from their experiments on a transonic fan stage.

2.9 Casing and Blade Tip Treatment

2.9.1 Casing Treatment In Axial Compressors

One of the most effective ways of improving the stall margin of a compressor is casing treatment: that is using a casing with a series of holes or slots above the blade tip.

Bettner & Elrod (1983), observed that at small clearances (about 1.5% of blade span) wall roughness causes a 6.5 to 7.5% reduction in the stall margin while for large clearances (about 3% of blade span), interestingly, a 2 to 4% stall margin

improvement was observed with a rough endwall. This shows that the sensitivity of the endwall boundary layer to the casing treatment is dependent on the tip clearance size. From the transonic fan stage experiments, Moore & Osborn (1977) observed that a casing accommodating skewed-slots over the blade row (Fig. 2.9.1.1) increased the stall margin and it was increased further by opening the slots. The skewed-slot configuration was also one of the configurations examined by Takata & Tsukuda (1977). From their experiments in a number of low speed axial-flow compressors, the authors found that this treatment gave the best improvement in the stall margin. In effectiveness the axial-slot configuration followed the skewed-slot while a circumferentially grooved casing had only little improvement in stall margin. These treatments found useful by Takata & Tsukuda are given in Fig. 2.9.1.2. However, unlike Moore & Osborn (1977), they concluded that with the application of the skewed-slot or axial-slot treatment the stall margin became uncoupled from the clearance size (i.e, changes in the clearance size did not affect the stall margin). From these results it is clear that the mechanism through which the casing treatment leads to improvements in stall margin must be understood, as a basis for choosing the most effective configuration.

Realizing this, Takata & Tsukuda (1977) performed detailed hot wire measurements, including within the slots of the treated casing. From their measurements behind the rotor they observed

Fig. 2.9.1.1 Casing Treatment, Skewed-Slot
(reproduced from Moore & Osborn (1977))

Fig. 2.9.1.2 Casing Treatments
(reproduced from Takata & Tsukuda (1977))

that the application of effective casing treatments removes the low energy fluid from the blade tip region. This prevents the blade tip from stalling prior to the other sections of the blade. Thus, with the application of casing treatment, the stall is seen at a lower flow rate and when it occurs, the whole blade span stalls simultaneously resulting in a rotating stall. From their measurements within the slots they were able to give the mechanism that delays the stall at the blade tip as follows:

"A part of the fluid in the main stream near the rotor tip enters the treatment slots and the backchamber, being pushed by the pressure surface near the trailing edge of the blades at every blade passing. High static pressure around the outlet of the blade row also helps the flow go into the slots. The fluid moves within the slots or the chamber towards the upstream and then is discharged at every blade passing as a thick jet from the part of the slots facing the upstream part of the blade chord into the middle of the blade spacing."

From the above given flow picture, it is easily seen that the jet out of the slot helps removing the low energy fluid close to the blade tip region as a result of momentum interchange. In fact, Takata & Tsukuda note that the effect of this jet is seen over a substantial radial portion of the annulus. They also state that this jet out of the slot does in fact work onto the main stream and increases the total pressure in some regions

which explains the reduced total pressure loss when casing treatment is used.

Now, in the light of the above given flow picture, the reason for the skewed-slot configuration to be effective while the circumferential grooves to be not, can easily be understood.

2.9.2 Casing Treatment in Axial Turbines

Because of the stalling problem in decelerating-flow stages, casing treatment has been used widely in fans and compressors. Even though stall is not a problem in accelerating-flow stages, casing treatment can be used to reduce the tip clearance effect on losses.

One of the early studies in this area was done by Kofskey (1961), who tested different casing treatments in a single stage turbine. The configurations tested are given in Fig. 2.9.2.1 and the resulting efficiency variations with increasing clearance height are given in Fig. 2.9.2.2. The trend in efficiency with tip clearance is essentially the same as discussed in section 2.7.1. Apparently due to the reduced blade tip unloading and reduced mass flow rate through the clearance, the labyrinth type configuration shows the best performance. The author explains the performance improvement of the recessed-casing configuration, compared with the smooth wall, by the fact that the blade height

(a) Reduced blade height.

(b) Recessed casing

(c) Shrouded rotor.

Fig. 2.9.2.1 Configurations Investigated By Kofskey (1966)

Fig. 2.9.2.2 Effect Of Tip Clearance On Performance At Design Equivalent Speed And Pressure Ratio (reproduced from Kofskey (1961))

is larger in the former case. It should also be noted that when the recessed-casing is used there is a reduction in the tip mass flow and blade tip unloading, even though it will not be as large as for the labyrinth type configuration. One more point worth mentioning is that according to the experiments by Haas & Kofskey (1977) on the recessed-casing configuration, the case where the rotor tip diameter is the same as stator tip diameter gives better performance than when the blade is extended in the groove. This may be due to the fact that when the blade height is extended into the groove, the work done by the blade will not increase in proportion to its length, since the blade portion within the groove sees a flow with relatively less energy. Haas & Kofskey also state that whether the recessed-casing extends after the blade trailing edge or ends right after the trailing edge does not have any effect on the efficiency.

2.9.3 Blade Tip Treatment

This is one of the areas where, according to the available literature, not much work has been done. As is well known, one way of reducing the tip leakage effects to very low levels is to use shrouded rotors. However, this has its own disadvantages, such as additional weight and the resulting increased radial stresses in the blades. Realizing these disadvantages, investigators have examined the use of a partial shroud (winglet). This is simply a small plate of some shape attached

to the blade tip (for example, see Fig. 2.9.3.1). Beside of winglet's apparent advantages on performance, discussed in the following paragraph, for the first turbine stages the problem of burnout at the pressure side edge of the winglet can reduce the life of the component. There might thus be a trade off between aerodynamic performance and component life.

Patel (1980) apparently conducted one of the first studies on the effect of a winglet on aerodynamic performance. The experiments were performed with an axial gas generator turbine with the winglet shape shown in Fig. 2.9.3.1. As was discussed in section 2.7.2, considerable underturning at the blade tip region was observed by a number of investigators (eg. Yokoyama (1961), Davino & Lakshminarayana (1982) and Takata & Tsukuda (1977)), indicating that in that region a relatively smaller portion of the fluid energy is converted into shaft work output. Patel's results (Fig. 2.9.3.2) show that, with the exception of a very small region close to the casing, the underturning in the outer 50% of the annulus is noticeably reduced. This indicates that with the use of winglets, the effect of the tip leakage flow on the pressure and suction side of the blade tip is considerably reduced. However, according to the results of Patel's study, unlike the casing treatments, the winglet does not reduce the rate of change of the efficiency with increasing clearance height.

Fig. 2.9.3.1 Partial Shrouded Blade
(reproduced from Patel (1980))

Fig. 2.9.3.2 Effect Of Partial Shrouds On The Radial Distribution Of The Stage Exit Swirl Angle
(reproduced from Patel (1980))

It is also important to determine whether the presence of winglets reduces the mass flow rate through the tip gap and/or the losses associated with the tip leakage flow. This aspect was investigated to some extent by Booth et al. (1982), who performed a number of experiments, some of which examined winglets, discussed in the following paragraph.

The experiments were performed in a single-side discharge rig, and a water table cascade with turbine blades (Fig. 2.12.1). The blade tip treatments examined during the discharge rig experiments are shown in Fig 2.9.3.3. The authors noted that the grooved blade tip configuration appeared to be the most effective one since it had the lowest discharge coefficient (Fig. 2.9.3.4). However, since the discharge coefficient is based on the actual pressure drop across the tip, using the discharge coefficient as a basis for comparing the configurations may give misleading results because a reduction in the leakage flow due to reduced pressure drop across the gap will not reflect in the value of the discharge coefficient. This fact was considered in the water-table cascade experiments, where the optimal tip treatment was further investigated; this time, in the analysis of the results the authors used the dimensional value of the leakage flow as a basis for comparison. The results indicated that the winglet is somewhat superior to the grooved configuration in reducing the leakage flow, since in addition to the reduced discharge coefficient, the driving pressure difference across the gap is

Fig. 2.9.3.3 Blade Tip Treatments Investigated By Booth et al. (Discharge Rig Experiments) (reproduced from Booth (1985))

Fig. 2.9.3.4 Results Of The Discharge Rig Experiments
(reproduced from Booth (1985))

Fig. 2.9.3.5 Tip Configurations Investigated By Booth et al. (Water-Table Cascade Experiments) (adapted from Booth (1985))

Fig. 2.9.3.6 Results Of The Water-Table Cascade Experiments
(reproduced from Booth et al. (1982))

also reduced. The results for the configurations shown in Fig. 2.9.3.5 are given in Fig. 2.9.3.6.

Wadia & Booth (1982) further continued the study on blade tip treatments both experimentally and analytically. The calculation scheme to determine the discharge coefficient for various tip treatment configurations analytically was simply the solution of the two dimensional incompressible laminar flow through the gap using time dependent finite difference equations. Except for the case of no tip treatment, the experimental discharge coefficients for various blade tip treatments were not predicted very accurately. As the authors noted, this might be a result of a number of shortcomings such as an accurate modeling of the singularities at the corners within the gap. Nevertheless, as the authors pointed out, this analysis can be taken as a starting point and be improved by eliminating the present limitations.

2.10 Tip Clearance Loss Analyses

In section 2.6.1 the tip clearance effect on performance was discussed. As was seen from the results obtained from various turbomachines, the variation of the efficiency drop due to tip clearance with clearance size is essentially linear. Therefore, it appears to be possible to give a simple correlation based on geometry only, i.e.:

$$\Delta\eta = -C_1 \left(\frac{t}{c} \right) \quad (2.10.1)$$

where C_1 is a constant. However, as was discussed in 2.6.1, this constant varies from one turbomachine to another, indicating the presence of factors other than the clearance height affecting the efficiency loss due to tip clearance. This clearly shows the necessity of more advanced models that account for all of the parameters effecting the losses due to tip clearance. The studies that have been done in this area are summarized in this section.

As far as the analysis of the tip clearance losses is concerned, Betz (1926) appears to have been one of the first to perform detailed studies in this area. In his analysis he evaluates the induced drag from the shed vortices at the blade trailing edge produced as a result of the gradient of the circulation distribution. Prandtl comments on this analysis and notes that the formation of the tip leakage vortex, i.e., the curling of the vortex sheet towards the blade tip, should be included. In reply to this comment, Betz states that assuming a flat vortex sheet or a sheet that is curled towards the blade tip should not make a difference as far as the lost energy is concerned. However, Betz's model implies that the flow direction in the tip clearance is parallel to the chordline which can only be valid where the blade aspect ratio and the tip clearance to chord ratio is large. Therefore this analysis may give

reasonable results only for fans with large blade aspect ratio and clearance size.

Rains' (1954) work is probably the first study where a reasonably accurate modelling of the flow and a good correlation of the losses were achieved. In fact, many subsequent studies were essentially improvements of his analysis. Therefore, a detailed summary of his work is given in the following paragraphs.

Rains (1954) stated that the application of the lifting line theory for predicting the tip clearance losses is not adequate. This is because the flow on a wing of high aspect ratio is not an adequate approximation to the flow on a blade of small aspect ratio with a tip clearance which is only a few percent of the chord length. He states that for a blade of small aspect ratio with tip clearance, the vorticity is mainly shed from the tip along the chord rather than from the trailing edge. Therefore, he suggests applying the Kutta condition to the edge of the clearance rather than to the trailing edge.

Since the pressure gradient along the blade is considerably small relative to the one across the clearance, the acceleration of the tip leakage flow can be assumed to be in the direction normal to the chord only. Based on this assumption Rains gives an expression for the calculation of the velocity component

normal to the blade chord, which is simply the Bernoulli equation applied between the conditions far upstream and downstream of the tip gap :

$$V_N = \left(\frac{2(P_1 - P_2)}{\rho} \right)^{\frac{1}{2}} \quad (2.10.2)$$

(for nomenclature refer to Fig. 2.12.2). Note that the above expression is valid only for the case where viscous forces are negligible. Rains, from his experiments with a single hydrofoil where endwall pressure measurements were taken along a contour following the blade shape, noted that this perfect fluid model where viscous forces are not taken into account is valid for gap to blade thickness ratios larger than 0.07. For clearances smaller than this, the pressure difference across the gap is almost completely balanced by the viscous forces. Certainly the Reynolds number must also have some effect on the maximum clearance size where viscous effects start to become dominant. Considering this point, Rains derived a more general parameter to be used for determining the ranges where the viscous and/or inertia forces are dominant: in order to have the same dimensionless blade tip pressure distribution from one Reynolds number to another, the nondimensional clearance velocity must be constant. This leads to the fact that the viscous pressure drop across the gap has to remain fixed also. Thus, calculating the

viscous pressure drop from laminar flow analysis, Rains arrived at the following parameter :

$$L = e^2 \epsilon Re \quad (2.10.3)$$

where e is the gap height to maximum blade thickness ratio, and ϵ is the maximum blade thickness to chord ratio at the blade tip. Based on his measurements, Rains concluded that for cases where this parameter is larger than 125, inertia forces are dominant, while for values smaller than 11 a pure viscous solution is required. As a second approach he derived an equilibrium laminar flow model which further confirms the ranges where friction and inertia forces are dominant. The above discussion implies that for the cases where this parameter is between 11 and 125, both inertia and viscous forces are effective. For this range Rains introduced another equation to be used for gap velocity calculation. This expression is derived from the Bernoulli equation with added loss terms that take into account the losses at the gap entrance (i.e., the separation bubble) and the turbulent or laminar friction loss within the gap. The resulting expression is as follows :

$$\frac{V_N}{V_\infty} = \left[\frac{\Delta C_p - (k + 2\frac{7}{4}C_f) \left(\frac{V_T}{V_\infty}\right)^2}{1 + k + (2\frac{7}{4}C_f)} \right]^{\frac{1}{2}} \quad (2.10.4)$$

where k is a constant that depends on the sharpness of the entrance corner of the clearance ($0 \leq k \leq 0.25$). Depending on whether the flow is laminar or turbulent, the skin friction coefficient, C_f , is calculated from one of the following equations:

for laminar flow approximation,

$$C_f \cong \frac{0.078}{\left[\frac{1}{\nu} (V_T^2 + V_\infty^2 \Delta C_p)^{\frac{1}{2}} \right]^{\frac{1}{2}}} \quad (2.10.5)$$

for turbulent flow approximation,

$$C_f \cong \frac{12\nu}{\left[V_T^2 + V_\infty^2 \Delta C_p \right]^{\frac{1}{2}}} \quad (2.10.6)$$

Rains (1954) also analyzed the effect of the relative endwall motion and from his experiments he concluded that the viscous drag effect of the endwall motion cannot be analyzed separate from the pressure difference, since the pressure field is considerably modified by the endwall motion. Therefore, he derived an expression applicable to clearance flow velocity calculation for the cases with endwall motion. The starting

equation for this derivation was again the Bernoulli equation with added loss terms mentioned in the previous paragraph. The resulting expression is as follows:

$$\frac{V_N}{V_\infty} = \left[\frac{\Delta C_p + \left(\frac{V'}{V_\infty}\right)^2 - (k + 2C_f) \left(\frac{V'}{V_\infty}\right)^2}{1 + k + 2C_f} \right]^{\frac{1}{2}} \quad (2.10.7)$$

where V' is the component of the free stream velocity normal to the blade and V'' is the component along the blade. C_f is still defined as in eqns. 2.10.5 and 2.10.6 with the exception that in those expressions V_T is replaced by V'' . It is worth mentioning that while Eqn. 2.10.7 is quite similar to Eqn. 2.10.4, it is not restricted to a certain clearance range. This implies that with relative endwall motion the viscous forces become more significant. However, Rains notes that the errors caused by neglecting the viscosity terms from Eqn. 2.10.7 do not exceed 20%, which indicates that for practical clearance sizes inertia forces are still dominant even when endwall motion is taken into account.

Based on these tip clearance flow computations, Rains (1954) introduced an expression for the tip clearance loss in which he assumed that the kinetic energy associated with the velocity component normal to the blade chord cannot be recovered. Even

	δ^*/h	θ/h	H
$t/c = 0.03175$	0.00731	0.00544	1.344
$t/c = 0.02845$	0.03837	0.02519	1.523
$t/c = 0.01981$	0.02820	0.02049	1.377

Table 4.3.2.1 Inlet Endwall Boundary Layer Parameters
For All Three Clearances Examined
($Re = 4.3E05$)

2

though he recognized that frictional effects within the gap also have some effect on the losses, he assumed them to be negligible for the clearance sizes seen in practice.

$$\Delta E = \frac{2 \left(\frac{t}{r_i} \right)}{\left(1 - \left(\frac{r_A}{r_i} \right)^2 \right) \cos(\beta_i^*)} \left[\frac{S_i}{c_i} \frac{\psi}{\cos(\beta_i^*)} \right]^{\frac{1}{2}} \times$$

$$\left[1 + \frac{c_i \cos^3(\beta_i^*)}{S_i \phi \psi} \left(\frac{t}{\delta^*} \right) \right]^{\frac{1}{2}} \quad (2.10.8)$$

The comparison of the theoretical results with the experimental ones from his pump experiments and from another reference fan showed very good agreement. The data covered the ranges where inertia and viscous forces are both important ($11 < L < 125$) and the range where inertia forces are dominant ($L > 125$).

Rains (1954) also developed a model for the flow outside the tip clearance where he considered the rate of rolling up of the vortex. The model, which is based on assumptions such as constant lift along the blade chord and inviscid flow, enables the calculation of the angle between the vortex axis and the chord line:

$$\beta_v = \tan^{-1} \left(\frac{4C_{Li}^{\frac{1}{2}}}{4 - C_{Li}} \right) \quad (2.10.9)$$

the circulation, associated with the vortex core:

$$\Gamma^* = e\epsilon \left(\frac{4 + C_{Lt}}{C_{Lt}} \right)^{\frac{1}{2}} t^{*0.72} \quad (2.10.10)$$

and the diameter of the core at a desired location:

$$\frac{r_c}{t} = 0.14 t^{*0.85} \quad (2.10.11)$$

where t^* , the dimensionless time used in the above equation, is defined as follows:

$$t^* = \frac{\left(\frac{z}{c_t} \right) (C_{Lt})^{\frac{1}{2}}}{e\epsilon} \quad (2.10.12)$$

Undoubtedly, one can argue on the validity of some of the assumptions used in this model. For example, constant lift distribution along the chord is probably not a very realistic assumption. Furthermore, as Rains himself points out, the size of the vortex is only a rough estimation because it is based on a stiff tip clearance jet assumption: since the jet velocity and

free stream velocity magnitudes are comparable, "stiff" jet is not a good approximation for the tip clearance flow. Even though, as the author states, this model could be improved, as will be discussed later in this section, in some of the recent prediction methods the size of the vortex is still obtained from this analysis.

Finally, it should be noted that all of Rains' study discussed so far is restricted to compressor and pumps, thus its validity for turbines has to be investigated.

2.10.1 Tip Clearance Loss Models Proposed As An Equivalent Drag Coefficient

Vavra (1960) introduced a simplified loss prediction method for axial compressors which uses the tip clearance velocity expression for stationary blade case, given by Rains (1954). Again, following Rains' argument, it is assumed that the tip clearance loss is the result of the kinetic energy normal to the blade chord not being recoverable. In the analysis a triangular blade loading is assumed, which is a reasonable approximation, particularly for compressor blades. However, even though the resulting expression is simpler than Rains' loss expression, it includes a contraction factor of the flow through the clearance (k) and another parameter that takes into account the flow resistance (Ω) in the clearance. These have to be determined

experimentally. The power loss is expressed as follows:

$$\Delta E = \frac{2\sqrt{2}}{5} k \Omega^3 \rho t c V_\infty^3 C_L^{\frac{3}{2}} \quad (2.10.1.1)$$

The author continued his analysis so as to express this loss in terms of a drag coefficient; the result is as follows:

$$C_{D,t} = \frac{4\sqrt{2}}{5} k \Omega^3 \frac{t}{h} C_L^{\frac{3}{2}} \quad (2.10.1.2)$$

For the constants k and Ω Vavra suggests the values 0.5 and 0.8 respectively. (Thus, the resultant constant in eqn. 2.10.1.2 is 0.29). The same expression was also used by Fujie (1962): based on his experimental data, Fujie suggested expressions for the profile, secondary flow and annulus drag coefficients. On the other hand, he pointed out that the tip clearance losses are affected by many variables, thus his data was not enough to derive an expression for these losses. For these losses he suggested Vavra's formula to be used. However, as Lakshminarayana & Horlock (1962) showed (Fig. 2.10.1.2), this expression does not provide very good results.

Similar to Vavra's analysis, Lakshminarayana & Horlock (1962) gave an expression where the tip clearance losses are predicted in terms of an equivalent drag coefficient. The authors note that their expression is applicable to small clearance to chord ratios: they suggest that for small values of the clearance to

chord ratio, unlike the finite wing case, some of the lift is retained at the blade tip as a result of viscous effects. This means that only a portion of the vorticity is shed at the blade tip. Therefore, they state that using the common lifting line theory, which assumes zero retained lift at the blade tip, is not adequate, particularly for small clearance to chord ratios.

Lakshminarayana & Horlock (1962) thus had to determine the amount of retained lift at the blade tip. They obtained this information by extrapolating the spanwise lift distribution curves to the blade tip. The retained lift obtained in this way was then nondimensionalized by the two-dimensional lift coefficient for the blade shape and was called the "retained lift coefficient". This retained lift coefficient together with the mean value of the blade bound vortex circulation enables the determination of the amount of vorticity shed from the blade tip, which is then used in the calculation of the induced drag.

In their induced drag model Lakshminarayana & Horlock (1962) assumed constant lift along the blade span, which implies that there is no vorticity shed from the trailing edge. It should be noted that this is a reasonable approximation for small aspect ratio blades only. Fig. 2.10.1.1 schematically shows the model used for this analysis. The authors compared the predicted induced drag values with the experimental ones which they obtained from a single aerofoil split at midspan. As can be seen

Fig. 2.10.1.1 Model Used By Lakshminarayana & Horlock (1962) For Induced Drag Prediction

Fig. 2.10.1.2 Comparison Of The Experimental And Theoretical Values Of C_{at} At Low Gap-to-Chord Ratios (reproduced from Lakshminarayana & Horlock (1962))

from Fig. 2.10.1.2, the agreement is quite good particularly when compared to the accuracy obtained with Vavra's (1960) analysis.

In 1965, based on their cascade experiments, the same authors introduced another expression for the induced drag coefficient. This analysis differs from the previous one in that the induced velocity is obtained from a different vortex system and, for better accuracy, the diameter of the tip vortex (determined experimentally) is taken into account when determining the limits for the spanwise integration of the induced drag. Furthermore, the authors observed that for moderate clearance-to-chord ratios the variation of the induced drag with the passage aspect ratio, which appears as a parameter in the expression, is quite small. Thus, as a result of simplifications, the induced drag coefficient was expressed as a function of the blade lift coefficient, blade aspect ratio and the retained lift coefficient only (Fig. 2.10.1.3). The authors note that for clearance sizes used in turbomachinery practice, the values of the retained lift coefficient can be approximated to be 0.5. Thus, their expression reduces to:

$$C_{D,i} = 0.7 \left(\frac{t}{s} \right) \frac{C_L^2}{A} \quad (2.10.1.3)$$

The authors noted that the agreement between the results of this equation and their experimental data is reasonably good.

Fig. 2.10.1.3 Variation Of C_{Dt} With Tip Clearance
 (reproduced from Lakshminarayana & Horlock
 (1965))

The expressions discussed so far, were suggested for compressors. Ainley & Mathieson (1951) gave an expression to be used for evaluating the tip leakage losses in turbines. The expression is as follows:

$$C_{D,t} = 0.5 \left(\frac{t}{s} \right) \frac{C_L^2}{A} \quad (2.10.1.4)$$

As is seen, this expression is very similar to that of Lakshminarayana & Horlock (1965) with the exception of the value of the constant (Ainley & Mathieson noted that this constant is suggested for plain tip clearance and should be replaced by 0.25 for shrouded blades).

The expression proposed by Meldahl (1941) differs from the ones discussed so far by the fact that the tip clearance drag coefficient is also related to the flow angle at the exit of the blade row :

$$C_{D,t} = 0.25 \cos(\alpha_2) \left(\frac{t}{s} \right) \frac{C_L^2}{A} \quad (2.10.1.5)$$

All the analyses discussed so far assumed a linear dependence of tip clearance loss on clearance size. Dunham & Came (1970) noted that the cascade data of Hubert (1960) suggested a slight deviation from this linearity. Thus, they modified the expression given by Ainley & Mathieson (Eqn. 2.10.1.4) and

Fig. 2.10.1.4 Variation Of $C_{D,t}$ With Tip Clearance For A Number Of Proposed Models (reproduced from Lakshminarayana (1985))

proposed the following expression:

$$C_{D,t} = 0.47 \frac{c}{s} \left(\frac{t}{c} \right)^{0.78} \frac{C_L^2}{A} \quad (2.10.1.6)$$

For shrouded blades the constant should be replaced by 0.37.

The authors noted that this expression showed good agreement with turbine results too.

Comparison of some of the loss models discussed in this section is given in Fig. 2.10.1.4.

2.10.2 Tip Clearance Loss Expressions Introduced In Terms of Percentage Reduction In Efficiency

In some of the tip clearance loss prediction studies the tip clearance effect has been expressed in terms of a percentage decrease in the efficiency of the stage.

Based on Vavra's analysis, Hesselgreaves (1969) derived this type of an expression: as is known, the reduction in the work coefficient as a consequence of the tip clearance flow is caused by three factors:

- i) Increase in drag due to the clearance flow
- ii) Reduction in blade loading
- iii) Reduction of blade size

Hesselgreaves noted that if the efficiency at zero clearance is sufficiently high and the work coefficient reduction due to (i) is comparable to the sum of the reductions due to (ii) and (iii), the decrease in efficiency can be written in terms of (i) only:

$$\Delta\eta \cong \eta_0 \frac{\Delta\psi_{(i)}}{\psi_0} \quad (2.10.2.1)$$

Then using the power loss expression given by Vavra (1960) (with the exception of flow resistance and gap contraction factor constants) he derived the following relation:

$$\Delta\eta \cong \left(\frac{t}{h}\right) f \quad (2.10.2.2)$$

where,

$$f = \eta_0 \frac{2\sqrt{2}}{5} \frac{1}{\psi_0 \phi} \left(\frac{V_\infty}{U_t}\right)^3 \frac{2S_t C_L^{\frac{3}{2}}}{1 + \frac{t}{h}}$$

is referred to as a sensitivity factor.

As was shown in Fig. 2.6.1.3, the agreement between the predicted efficiency loss and experimental results is reasonably good. The author also commented on the triangular blade loading assumption used by Vavra: he stated that assuming a uniform loading instead of a triangular one causes only a reduction of 11% in the power loss due to tip leakage. Thus he concluded that

the type of assumed loading is apparently not very critical.

Another study where the tip clearance losses are expressed in terms of a decrease in efficiency is the one of Amann et al. (1963). Based on the following assumptions, Amann proposed the expression given in eqn. 2.10.2.3 to be used for turbines.

- The mean angular momentum changes are representative of the overall stage performance.
- The whirl at the turbine exit is very small.
- The stator has zero clearance.
- In the tip clearance section the flow is essentially undeflected.

$$\Delta\eta = \frac{-2\pi r_t t}{A_{throat}} \eta_o \quad (2.10.2.3)$$

With a reasonable approximation this expression can be simplified as follows:

$$\Delta\eta = \frac{-r_t}{r_m \cos(\alpha_2)} \eta_o \frac{t}{h} \quad (2.10.2.4)$$

Based on experimental investigations in a small turbine, Rogo (1968) noted that the above given expression predicts the experimental results (at design speed and work conditions) quite

accurately, provided the clearance size is not large.

Kacker & Okapuu (1982) also suggested Amann's expression with the exception that they reduce the result obtained from Eqn. 2.10.2.3 by 7%. They noted that the results correlated with most of the available experimental data within 15%.

As was noted in section 2.6.1, degree of reaction at the blade tip appears to be an important parameter affecting the magnitude of the tip clearance losses. Roelke (published by Glassman (1973)) compared some of the experimental results available in the literature to the predicted ones using the correlation given by Hong & Groh (1966) (Fig. 2.10.2.1) where the effect of reaction on the tip clearance losses is taken into account. (In the figure, W and V are the relative and absolute velocities respectively). Roelke noted that the predictions were reasonably accurate for clearance sizes seen in practice.

Another correlation for the tip clearance losses was proposed by Craig & Cox (1970-71). The authors considered a special application where a sudden enlargement is present between stationary and moving blade rows (see Fig. 2.10.2.2). This application is frequently seen in steam turbines. While there is a loss due to the sudden enlargement, the static pressure reduction caused by the enlargement will result in a considerable decrease in reaction, thus reducing the losses due to the tip gap

Fig. 2.10.2.1 Effect of Reaction On the Efficiency Variation With Tip Clearance
 (reproduced from Glassman (1973))

Fig. 2.10.2.2 Variation of The Efficiency Debit Factor With The Rotor Tip Leakage Coefficient
(reproduced from Craig & Cox (1970-71))

flow. The correlation is as follows:

$$\Delta\eta = \frac{-1.5F_k r_t}{r_m \cos(\alpha_2)} \eta_o \frac{t}{h} \quad (2.10.2.5)$$

where F_k is a factor that accounts for the effect of reaction and recess on the tip clearance loss. The correlation for F_k is given in Figure 2.10.2.2. As is seen, at zero reaction the efficiency drop due to tip leakage appears to be nonzero. The authors explain this with the fact that some windage loss from the shroud band still remains at zero clearance.

As a continuation of the work by Lakshminarayana & Horlock (1965), Lakshminarayana (1970) introduced a semi-empirical expression for calculating the efficiency drop due to tip clearance effects. He noted that the losses presented in the form of an induced drag coefficient do not account for all of the losses since there is substantial spanwise flow in the blade surface boundary layer near the tip. Therefore, he also included this effect in his semi-empirical expression for efficiency decrease due to tip leakage. The resultant expression is as follows:

$$\Delta\eta = \frac{0.7\psi}{\cos(\alpha_m)} \left[1 + 10 \left(\frac{1}{\cos(\alpha_m)} \frac{\phi h t}{\psi c h} \right)^{\frac{1}{2}} \right] \frac{t}{h} \quad (2.10.2.6)$$

The author compared a number of experimental results from pumps, compressors and turbines with predicted values (Fig. 2.10.2.3), which showed quite good agreement. However, as can be seen from Fig. 2.10.2.4, the results of one recent study (Inoue et al. (1986)) are not predicted very accurately. Lakshminarayana (1970) noted that even though his comparisons gave good agreement, there are a number of parameters that are not included in the correlation, such as blade thickness at the blade tip, Reynolds number and endwall boundary layer thickness, and are likely to influence the losses. The disagreement seen in Fig. 2.10.2.4 might be a result of this. As will be discussed at the end of the next section, the value of the retained lift coefficient might also be a reason for the disagreement.

2.11 Prediction of the Blade Surface Pressures Near the Blade Tip

The lift coefficient at the blade tip appears as a parameter in the loss prediction methods. Therefore, it would appear to be important to be able to predict the correct value of the local loading at the tip. In the case of small aspect ratio and finite clearance size, the suction surface pressure distribution is substantially affected by the presence of the tip leakage vortex. Therefore, it is not possible to use the usual lifting surface

a)

b)

c)

Fig. 2.10.2.3 Stage Efficiency Variation With Clearance Size
 a) Axial-Flow Compressors
 b) Axial-Flow Fans
 c) Axial Pump And Turbine
 (reproduced from Lakshminarayana & Horlock (1970))

Fig. 2.10.2.4 Efficiency Variation With Tip Clearance
(adapted from Inoue et al. (1986))

theory for predicting the pressure distribution on a turbomachinery blade. Yokoyama (1961) introduced a quite simple method for determining the suction surface pressure distribution. In his calculation he assumed a linear variation in bound vorticity along the chord line, which corresponds to a triangular chordwise lift distribution. The tip leakage vortex is assumed to be a continuation of the bound vortex which implies that none of the vortex lines cross the gap between the blade tip and the endwall (i.e., no retained lift at the blade tip is assumed). Two different models were used for the vortex shedding at the blade tip. In one of them the vortices are taken to be parallel to each other and are aligned with the main stream direction. In the other one, they join a vortex which starts from the leading edge and is in the main stream direction (see Fig. 2.11.1). Then, the suction surface velocity is determined by superimposing the velocities induced by the bound vortex and the tip leakage vortices. Comparison of the results with experimental data showed reasonable agreement for both spanwise and chordwise pressure distributions particularly when the tip vortices were assumed to join the vortex which starts from the leading edge.

Probably the agreement of Yokoyama's model with experimental data could be improved if the vortex starting point were taken as approximately $1/3$ of the chord length from the leading edge since, despite the slight shifts with various factors, that is the approximate location where the tip leakage vortex starts to

Fig. 2.11.1 Yokoyama's (1961) Models For Blade Suction Surface Pressure Distribution Prediction

form. In fact, in the potential vortex model introduced by Lakshminarayana & Horlock (1965), which was used for predicting the blade pressure distributions, the vortex was started at 25% chord length from the leading edge. In this model the circulation distribution at the blade tip was varied linearly with x/c and the circulation in the first 25% chord length region was assumed to be retained at the blade tip (see Fig. 2.11.2). Another improvement in Lakshminarayana & Horlock's model (compared to the model used by Yokoyama) is that the potential vortex is not only at an angle to the suction surface but is also inclined to the blade tip. Considering the conical shape of the vortex, this is certainly more realistic. The two angles were determined experimentally. One more respect in which Lakshminarayana & Horlock's model is more powerful than Yokoyama's model is that the former is able to predict the pressure distribution on both sides of the blade while Yokoyama notes that the boundary condition that he used in his model is not applicable for predicting the pressures on the pressure surface of the blade.

Since Yokoyama was not able to predict the pressure distribution on the blade pressure surface, in order to overcome this shortcoming he introduced a lifting line theory which is modified from Prandtl's original lifting line theory so as to account for the tip leakage vortex effect (Fig. 2.11.3). Particularly close to the blade tip, the agreement between the

Fig. 2.11.2 Lakshminarayana & Horlock's Model For Blade Surface Pressure Distribution Prediction (reproduced from Lakshminarayana & Horlock (1985))

Fig. 2.11.3 a) Model Used In Prandtl's Lifting Line Theory
 b) Yokoyama's Model
 (reproduced from Yokoyama (1961))

calculated spanwise lift distribution and experimental data is not very good; nevertheless the expected trend is predicted.

Lewis & Yeung (1977) reviewed a number of methods that have been used for predicting the lift distribution (Fig. 2.11.4): the vortex lattice method has been successfully used in the lift distribution prediction for large aspect ratio lifting surfaces. However, it is not suitable for small aspect ratio blades since it does not account for the presence of the cumulatively developed rolled up tip vortices. Furthermore, the lift distribution, normalized against the overall lift coefficient, predicted by the vortex lattice method, is not affected by the angle of attack which does not agree with the experimental results for turbomachine blades.

The tip vortex method shown in Fig. 2.11.4 appears to give better results as far as the aspects noted in the previous paragraph are concerned. In fact, this model, with the exception of the trailing vortices, was the basis of one of the two models used by Yokoyama (1961) to predict the blade suction surface pressure distribution. However, the tip vortex method fails to predict the localized increase in the loading close to the blade tip, caused by the tip vortex located against the suction surface of the blade. As a solution to this problem Lewis & Yeung (1977) suggest a concentrated tip vortex method (Fig. 2.11.4) which will be discussed later in this section.

(A) VORTEX LATTICE METHOD

(B) TIP VORTEX METHOD

PLAN VIEW

(C) CONCENTRATED TIP VORTEX METHOD

Fig. 2.11.4 Diagrammatic View Of Different Models
(reproduced from Lewis & Yeung (1977))

During their work on models to be used for predicting the loading distribution, Lewis & Yeung (1977) performed some experiments with an isolated aerofoil. The static pressure on the endwall was measured along a contour following the blade surface edge (see Fig. 2.11.5). From these measurements they determined the retained lift at the endwall and formed the retained lift coefficient as defined by Lakshminarayana & Horlock (1962). Their data appear to be close to that determined at the blade tip by Lakshminarayana & Horlock (1962). Since Lewis & Yeung's (1977) data covered a larger gap to chord ratio range, following Lakshminarayana & Horlock's (1962) correlation, they presented another correlation for the retained lift coefficient. Both correlations together with experimental data are given in Fig. 2.11.5. Even though the correlations appear to give similar results, Lewis & Yeung's correlation can be criticized since data for high gap to chord ratios were also taken into account whereas Lakshminarayana & Horlock indicate that this type of retained lift calculation is only valid for low gap to chord ratios.

Using this retained lift coefficient, Lewis & Yeung (1977) modified the tip vortex method given in Fig. 2.11.4 such that only part of the bound vorticity at the blade tip is shed. They also used a different expression for calculating the angle between the shed vortex and the blade chord. This improved tip vortex model is shown in Fig. 2.11.6. Comparison of the

Fig. 2.11.5 Retained Lift Coefficient Variation With Clearance Size (reproduced from Lakshminarayana (1985))

Fig. 2.11.6 Lewis & Yeung's Modified Tip Vortex Method
(reproduced from Lewis & Yeung (1977))

predictions with the experimental results of Lakshminarayana & Horlock (1962) shows that the modified tip vortex method gives much better results than the vortex lattice and the original tip vortex methods, particularly at small clearances where the amount of retained lift at the blade tip is significant.

As noted by Lewis & Yeung, the concentrated tip vortex method (Fig. 2.11.4) is probably more realistic than the ones discussed so far. With the exception of the trailing vortices, and the strength of the tip vortex (note that in the concentrated vortex model the tip vortex starts to shed at the leading edge which means all the circulation at the blade tip is shed), this is in fact the model used by Lakshminarayana & Horlock for blade surface pressure distribution prediction (Fig. 2.11.2), discussed earlier.

In the work of Lakshminarayana (1970), the author noted that the potential vortex model used for predicting the blade surface pressure distribution (Fig. 2.11.2) is not realistic enough to enable prediction of the blade-to-blade outlet angle and loss distribution at the tip region of the blade. Therefore, the author presented another model (see Fig. 2.11.7). In this calculation scheme the diameter of the tip leakage vortex is obtained from Rains' (1954) analysis. From his comparisons with various experimental results he concluded that the model predicts the over and under turning quite accurately while the loss

distribution is predicted only qualitatively. A qualitative agreement between the measured and predicted flow angle was also observed for Inoue et al.'s (1986) measurements at the exit of an axial compressor. It should also be noted that in this analysis the determination of the circulation associated with the tip leakage vortex is based on an inviscid tip leakage flow with a stationary blade. Gearhart, based on his experimental results (Gearhart (1966)) commented on this point: he noted that, due to viscous drag effect, the endwall motion has a significant effect on the leakage mass flow rate. Therefore, it is likely that the circulation associated with the leakage vortex (thus the retained lift coefficient) is altered by the endwall motion, and this effect should be included into the analysis. In fact, from the data obtained in a compressor rotor by Inoue et al. (1966), it appeared that the measured circulation associated with the tip leakage vortex is much larger than the one predicted using Lakshminarayana & Horlock's (1962) correlation for the retained lift coefficient. This is an expected result since in compressors the endwall motion increases the tip leakage mass flow rate which will likely result in a stronger leakage vortex. Thus, the effect of endwall motion on the retained lift coefficient is one aspect that should be investigated in the near future.

2.12 Modeling of the Flow Inside the Tip Gap

In section 2.10 a review of the loss models was given. The analyses that were based on Rains' (1954) assumption that the kinetic energy associated with the normal component of velocity of the leakage flow is lost, require a model for the velocity field within the gap. As discussed, one such model was introduced by Rains (1954) and is simply based on a tip leakage velocity calculation using Bernoulli's equation, with the assumption that the tangential velocity is conserved across the gap. Lakshminarayana's (1970) modeling of the flow out of the clearance (see previous section) was based on a leakage flow model in which a uniform leakage was assumed, which is not really the best approximation.

As indicated in the previous paragraph, even though a few leakage models exist, they were introduced as part of other calculation schemes, such as loss correlations and modeling of the flow emerging from the clearance region. Although some of these calculation schemes appeared to be successful, this does not necessarily mean that the leakage flow is modeled accurately and in none of these studies was this analyzed in detail. Even though the prediction of the losses and the flow disturbance near the blade tip is important, since the main objective is to reduce the negative effect of the tip clearance flow on the performance of the machine, there is an obvious need for a model which

enables the prediction of the flow within the tip clearance.

This could lead to configurations which reduce the leakage flow and/or the losses associated with it.

Booth et al.'s (1982) appears to have been the first study where the leakage flow was modeled for the above indicated purpose. The authors used Rains' (1954) inviscid analysis (see section 2.10) as the basis for their model, since their theoretical and experimental analyses seemed to support the assumptions built into that analysis (i.e, the dominance of inertia forces for practical clearance sizes, the conservation of tangential momentum across the clearance, etc.). In their experiments they used three test sections which are shown in Fig. 2.12.1. One of the interesting results of the experiments with the single-side discharge rig is that the discharge coefficient (defined for the tip leakage mass flow rate) is independent of the clearance size. This appears to contradict Graham's (1986) results which, as was noted in section 2.5, showed a nonlinear variation of the leakage mass flow rate with clearance size. The results presented in this thesis support Graham's observation, as will be discussed in detail. From their double-sided discharge rig Booth et al. concluded that the effect of the suction side velocity on the leakage flow was of second-order. This helps to justify the assumption of conservation of the tangential momentum through the gap. Finally, they performed some experiments in a water table cascade

Figure 2.12.1 Water rig configurations (reproduced from Booth et al. [1982])

with turbine blades where they measured the leakage flow velocity and direction using dye clusters and a high speed camera.

However, as noted by the authors, there were some errors due to this measurement technique. One of the striking results was the straight streamlines through the gap, which they then used in their leakage model. More information on the model itself is given in section 7.2, where it is examined in detail in the light of the present measurements.

Very recently, Moore & Tilton (1987) presented two theories for predicting the pressure distribution through the gap as well as experimental data which they obtained from measurements in a rectilinear turbine cascade with 2.1% clearance-to-span ratio. In addition to the work discussed in the previous section, Rains (1954) also introduced an expression based on potential theory which, once the tip gap velocity is determined using Bernoulli's equation (see Rains' analysis discussed in section 2.10), can be used to determine the pressure distribution within the gap. Rains did not go into the details of this theory since his main objective was to obtain a loss correlation and the gap velocity obtained from Bernoulli's equation was good enough for that purpose. Moore & Tilton analyzed this potential theory and concluded that it contradicts the one given by Rayleigh in 1876. Their further analysis showed that the discrepancy was in Rains' analysis and they presented the correct expression.

Undoubtedly, as seen in Fig. 2.12.3, the real flow is quite different from the ideal one given in Fig. 2.12.2. Therefore, Moore & Tilton used the potential theory only for the flow prediction up to the clearance entrance. The experimental pressures, both from the endwall and blade pressure surface, appeared to be predicted quite accurately. In order to predict the whole gap flow, the authors presented a second method which was a two-dimensional potential flow theory combined with a mixing analysis. With this model the flow up to the point where the stream tube inside the gap reaches its minimum height is predicted quite accurately. Downstream of this section, the final pressure value after the pressure rise due to mixing is also predicted accurately. However, in the intervening region of rising pressure the agreement is not very good.

Moore & Tilton calculated the discharge coefficient which appeared to be close to the value of about 0.8 quoted by Booth et al. (1982). They were also able to predict this discharge coefficient from an expression obtained from the latter theory mentioned above. The predicted discharge coefficient appears to be reasonably accurate. The theoretical discharge coefficient is a function of the contraction ratio only. The theory gives a constant contraction factor of 0.611 so that the discharge coefficient has a constant value of 0.8435. However, it should be mentioned that the present measurements clearly show that the size of the separation bubble on the blade tip, relative to the

Fig. 2.12.2 Rains' Idealized Tip Gap Flow Model
(reproduced from Moore & Tilton (1987))

Fig. 2.12.3 Actual Tip Gap Flow
(reproduced from Moore & Tilton (1987))

clearance height changes with clearance size, resulting in different discharge coefficients for different clearance sizes. This fact is also important as far as the other theories discussed earlier in this section are concerned since the discharge coefficient is one of the essential parameters in those theories. In Moore & Tilton's case the experimental value of the contraction factor appeared to be close to the theoretical one, explaining the good accuracy of the predicted pressure distributions. However, in cases where the contraction factor deviates significantly from the theoretical one, the results should not be as good.

Realizing the importance of understanding and predicting the leakage flow within the tip clearance, the study presented in this thesis is oriented to detailed measurements in the tip clearance. These results are then used for assessing the validity of the leakage model of Booth et al. (1982) and an attempt is also made on modifying this model.

3. Description of Apparatus

3.1 Annular Wind Tunnel

An annular wind tunnel consisting of a fan driven by a variable speed DC motor is used as the wind source for the experiments. A straight annular diffuser with an area ratio of 2.72 and an equivalent cone angle of 14° is used to convert the dynamic pressure into static pressure. The outlet of the annular diffuser accommodates a honeycomb consisting of cells with 9.5 mm width and 76 mm depth which is used to remove the swirl from the flow. The diffuser discharges into a settling chamber that includes three stainless steel screens of 7.9 mesh/cm with an open area ratio of 0.58, for the purpose of reducing the size of the eddies present in the fan outlet flow. Each of these three screens is made of a single layer except the screen closest to the fan outlet on which the number of layers is increased to three at its centre in an attempt to spread the flow uniformly over the settling chamber. A cross sectional view of the annular wind tunnel, adapted from Sjolander (1975), is given in Fig.

3.1.1.

The data for the largest tip clearance examined ($t/c = 0.03175$) was taken with a Budworth two-stage axial compressor as the wind source (see item 1 in Fig. 3.1.1) which was capable of supplying a maximum flow rate of about 4 kg/sec at a maximum total pressure

1	Axial Compressor	4	Diffuser	7	Bleed Ring
2	Settling Chamber	5	Honeycomb	8	Transition Section
3	Test Cascade	6	Screens		

Fig. 3.1.1 Annular Wind Tunnel
(Adapted from Sjolander (1975))

rise of about 500 mm of water. However, for the other two clearances considered ($t/c = 0.02845$ and $t/c = 0.01981$), due to the failure of the axial compressor, a centrifugal fan with specifications similar to those of the axial compressor was used instead.

The circular settling chamber outlet is connected to the planar test cascade inlet with a fiberglass transition section. Because of the cross sectional area increase of 1.2 through this transition section, the flow experiences some diffusion before entering the test cascade.

More information on the annular wind tunnel components and detailed dimensions can be found in the work of Amrud (1985).

3.2 Test Cascade

The planar cascade test section, shown in Fig. 3.2.1, was designed by Amrud (1985) for the purpose of detailed investigations into tip leakage flows in turbines. The test section is 675 mm wide and 203.2 mm deep and accommodates a row of five turbine blades. The blades are mounted on a 7.9 mm thick steel backwall which is essentially the main support of the test section. The front endwall is made of 12.7 mm thick plexiglass, enabling oil and smoke flow visualization studies. Also, it is hinged on the test section allowing easy access to the blades.

Fig. 3.2.1 Test Rig (Adapted from Amrud (1985))

The periodicity of the flow in the blade row is adjusted using the side flaps and tailboards (see Fig. 3.2.1). The blades of 250 mm chord and 202.3 mm span, manufactured during the work of Amrud (1985), are mounted to the backwall with a stem-collar arrangement and are scaled on the turbine rotor blade geometric specifications obtained from Pratt & Whitney Canada. Except for a few slight modifications, all the dimensions related to the blade row are essentially the same as described by Amrud. One of the differences is the modification of the blade tips.

Subsequent to Amrud's work, the thin seal at the tip of the instrumented blade was damaged. Therefore, 2.3 mm thick blade shaped aluminum pieces were mounted on to the blade tips resulting in a small increase in the blade span. Another modification was the slight change of the blade incidence. For the test cases described in this report it was set to -10.89° with an accuracy of $\pm 0.2^\circ$. Since on this cascade the only way to change the blade incidence is to rotate each blade about its mounting stem which is attached to the blade at about $1/3$ chord, for the revised incidence the stagger angle became 38.34° . For easy reference, all changed and unchanged geometric parameters related to the blade row are given in Appendix A.

The plexiglass endwall portion around the second blade from the test section bottom is instrumented with a closely-spaced grid of static pressure taps of 0.5 mm diameter, enabling detailed endwall static pressure measurements (Fig. 3.2.2). The centre

Fig. 3.2.2 Endwall Static Pressure Tap Locations

blade, which is made of aluminium, is instrumented with 14 rows of static pressure taps of 0.51 mm diameter, each row consisting of 37 pressure side and 36 suction side taps. Exceptionally, at the midspan row close to trailing edge, the last three suction surface taps are not drilled due to technical limitations.

Because of leakage or blockage problems some of the taps could not be used in the measurements. These are specified in Appendix B where all blade tap co-ordinates are included. As a result of the blade tip modification described above, the blade static tap row locations relative to the blade tip are slightly different from the ones quoted by Amrud (1985). The revised locations are specified in Appendix B. Note that during the experiments only one chordwise row of static taps could be used at a time, while the other rows were sealed, since on each blade surface the taps at the same chordwise location are connected to the same channel inside the blade.

3.3 Three-Hole Probe

A three-hole probe was used for velocity magnitude, flow angle and total pressure measurements within the tip clearance. As will be discussed in Chapter 6, apart from the small scale three dimensional flow structure close to the blade tip, the streamlines within the clearance lie largely in planes parallel to the blade tip, thus allowing reliable three-hole probe measurements. A more detailed discussion on the accuracy of the

three-hole probe measurements is included in section 3.4.2. As can be seen from Fig. 3.3.1, the probe head is only 0.7 mm thick and 2.0 mm wide, which, for the examined clearance height range ($t = 4.95$ mm to 7.94 mm), enabled measurements to be made with reasonably little interference to the flow through the tip gap. Although a seven-hole probe was also available, it was not possible to use it for measurements within the clearance because of its relatively large diameter of 2.4 mm. The stem carrying the three-hole probe was supported by a traversing gear mounted to the back plate. The traversing gear allowed translation in pitchwise and spanwise directions and rotation in the plane parallel to the cascade endwall. This gave access to any location within the tip clearance except for a small region of about 6% of chord length which could not be measured because of the limited number of vertical slots filled with aluminum sliders on the back plate which were used for access to the traversing gear through the backwall. Nevertheless, this shortcoming was not very significant since the region was close to the trailing edge where the flow regime is not expected to change rapidly in the chordwise direction.

3.4 Three-Hole Probe Calibration

At the beginning of the experiments the three-hole probe was calibrated for yaw angles over the range of $\pm 70^\circ$ with an interval of one degree. The probe was calibrated in a jet flow

Fig. 3.3.1 Three-hole Probe

discharging into the atmosphere, allowing the dynamic pressure to be calculated from the total pressure of the jet flow and the atmospheric pressure in the environment. Total pressure was also used as reference pressure for the three probe pressures. Since at that time a data acquisition system was not available, the probe pressures and the dynamic pressure were read from two 55D 31 type DISA voltmeters with their time constants set to 3 seconds. The reason for using two voltmeters at the same time was to ensure that the dynamic pressure remained the same while measuring all three probe pressures which was required for data reduction. The first set of data was collected for a dynamic pressure of about 1700 Pa. In order to determine whether the calibration is sensitive to variations in the local dynamic pressure, a second set of measurements was taken for a dynamic pressure of about 500 Pa. After all the data was obtained, it was processed according to the method outlined by Lewis (1966) and the following coefficients were formed:

$$K_1 = (P_1 - P_s)/q$$

$$K_{12} = (P_1 - P_2)/q$$

$$K_{13} = (P_1 - P_3)/q$$

$$K_{23} = (P_2 - P_3)/q$$

$$K_{\phi 2} = (P_1 - P_2)/(P_1 - P_3)$$

$$K_{\phi 3} = (P_1 - P_3)/(P_1 - P_2)$$

where the hole numbering system is shown in Fig. 3.3.1. The three-hole probe can only be used for measuring the yaw angle which, for the rest of this chapter, will simply be referred to as the flow angle. However, the effect of pitch angle on the measured quantities will also be examined in section 3.4.2.3.

3.4.1 Three-hole Probe Data Reduction Using the Calibration Curves

During the reduction of experimental data the sign of the flow angle relative to the probe is determined by comparing the probe pressures P_2 and P_3 and the magnitude of the angle is then calculated using one of the coefficients $K_{\phi 2}$ and $K_{\phi 3}$. The reason for defining two coefficients for the same purpose is to enable better accuracy in extracting the flow angle. As can be seen from the plot of $K_{\phi 2}$ versus flow angle (Fig. 3.4.1.1), for flow angle ranges other than -50° to 0° and 50° to 70° this coefficient is not suitable. Therefore, for the remaining part of the flow angle range considered, the coefficient $K_{\phi 3}$ is used instead (Fig. 3.4.1.2).

After the flow angle is determined, the dynamic pressure is

Fig. 3.4.1.1 K_{ϕ_2} VS. FLOW ANGLE

o Low Dynamic Pressure
+ High Dynamic Pressure

Fig. 3.4.1.2 K_{θ} VS. FLOW ANGLE

calculated from one of the coefficients K_{12} , K_{13} or K_{23} . As can be seen from the K_{12} versus flow angle curve (Fig. 3.4.1.3), for positive flow angles the change in the curve with dynamic pressure changes is relatively significant which reduces the accuracy in extracting the dynamic pressure from this curve. The same case is seen at the negative flow angle portion of the K_{13} versus flow angle curve (Fig. 3.4.1.4). Therefore for positive and negative flow angles K_{13} and K_{12} are used respectively. There is an exception to this whereby these coefficients get close to zero. Since in the calculation of the dynamic pressure the coefficient appears as the denominator, if it is close to zero, a small change in its value will result in large changes in the dynamic pressure. Undoubtedly, this will increase the uncertainty in the calculated dynamic pressure. Therefore, for the regions where the coefficients K_{12} and K_{13} are close to zero, which correspond to -30° to -10° and 10° to 30° flow angle ranges, K_{23} is used instead (Fig. 3.4.1.5).

Once the dynamic pressure is calculated, coefficient K_1 is used to determine the static pressure (Fig. 3.4.1.6). Even though K_1 is used for the whole flow angle range considered (-70° to 70°), the range is divided into five sections for purposes of fitting polynomials to the data using the method of least-squares. Similarly, least-square curve fitting is done to all other curve portions described above which will be used in the data reduction. The order of the fitted polynomials were

0 Low Dynamic Pressure
+ High Dynamic Pressure

Fig. 3.4.1.3. K_{12} VS. FLOW ANGLE

0 Low Dynamic Pressure
+ High Dynamic Pressure

Fig. 3.4.1.4 K_{13} VS. FLOW ANGLE

○ Low Dynamic Pressure
+ High Dynamic Pressure

Fig. 3.4.1.5 K_{23} VS. FLOW ANGLE

Fig. 3.4.1.6 K_1 VS. FLOW ANGLE

determined by trial and error and were typically 6 to 8. The fitted curves are entered into the three-hole probe data reduction program for which the source code is given in Appendix C.

As was indicated earlier, the effect of the dynamic pressure changes on the calibration curves, which is presumably a Reynolds number effect, was determined by taking two sets of calibration data, each for a different dynamic pressure. The portions of the curves used in data reduction for which changes with the flow rate can be seen on the plots are as follows :

- (a) K_1 within flow angle ranges -70° to -50° and 50° to 70° ,
- (b) K_{12} within flow angle range -70° to -50° ,
- (c) K_{13} within flow angle range 50° to 70° .

For these curve portions least-square curve fitting was done for both flow rates and the data reduction program was prepared so that depending on the value of the dynamic pressure the closest one is used. Note that K_{12} and K_{13} are in fact used in the dynamic pressure calculation itself; therefore, a short iteration is necessary. Undoubtedly, in this procedure an approximation is present since the calibration data was taken for only two different dynamic pressures.

3.4.2 Accuracy of the Three-hole Probe Measurements

In this section a substantially detailed analysis of the accuracy of the three-hole probe measurements is given. The results of this analysis indicated that the quantities obtained from the probe measurements are quite accurate.

3.4.2.1 Errors In Measured Flow Angle and Dynamic Pressure

To the curve portions used in data reduction which, according to the plots, appear to remain unaltered with changes in the flow rate, least square curve fitting was done for the low flow rate data since it appeared to be less scattered. When the raw calibration data for low flow rate is then fed back into the data reduction program, the flow angle matches within $\pm 0.5^\circ$ and the error in the measured dynamic pressure is less than 1% of the actual local dynamic pressure. On the other hand, if the high flow rate calibration data is reduced with those calibration curves, the errors in the measured flow angle and dynamic pressure are somewhat higher: for example, the error in the measured flow angle is up to 1° . Although this is still a small value, the important point is that the error is not in the form of scatter but appears either as a systematic underestimate or as an overestimate within different flow angle ranges. This indicates that, even though on the plots it is not obvious, the portions of the $K_{\phi 2}$ and $K_{\phi 3}$ curves that are used in data

reduction do slightly alter with changes in the flow rate. This change in the curves is presumably small within $\pm 30^\circ$ flow angle range since the error is less than 0.5° (note that the error is always on the positive side). Out of this range the error reaches the peak value of 1° as was noted above.

Even though an error of 1° in the measured flow angle is quite small, it causes measured dynamic pressure errors up to 10%. The reason for not giving an exact error value is that this error also depends on the local slope of the curve from which the dynamic pressure is calculated. Since, as was mentioned above, the error seen in the flow angle was systematic, this in turn results in systematic errors in the dynamic pressure. The results showed that in the flow angle ranges -50° to -30° and 30° to 50° , the errors in the measured dynamic pressure reach high magnitudes which closely ties into the error distribution that was seen in the measured flow angles. In the flow angle range -50° to -30° the measured flow angle is about 1° less than the actual value causing a dynamic pressure error of about +10% while in the flow angle range 30° to 50° , the error in the flow angle is about $+0.8^\circ$ which results in an average dynamic pressure error of -4%. In the remaining parts of the calibrated flow angle range, the maximum error in the dynamic pressure is +2%.

The errors in measured dynamic pressure will of course result in errors in the mass flow rate through the tip gap. In order to

determine this error in the mass flow rate, a second set of calibration coefficients based on the high flow rate data was obtained. Then the three-hole probe data for $t/c = 0.01981$ was reduced using both of the calibration curve sets. The difference between the calculated total mass flow rates was found to be less than 1%. Considering the peak values of the dynamic pressure errors discussed above, this error is quite small and can be explained as follows:

As was noted above, the dynamic pressure errors are high only in certain flow angle ranges. Therefore, presumably for most of the tip clearance three-hole probe measurements the flow angle relative to the probe was out of those ranges. In order to justify this argument, the chordwise distributions of the mass flow rate, based on the two different calibration curve sets noted above, were compared. The comparison showed that only in a very small chordwise region after midchord the flow angle relative to the probe was in those ranges. However, it should be noted that in a flow field where most of the measurements fall into the flow angle ranges where the errors are high, the results might be very misleading.

3.4.2.2 Three-Hole Probe Recalibration

At the end of the experiments the probe was recalibrated for the same flow rates as in the first calibration. This time a

computerized data acquisition system was used resulting in less scattered data for both low and high flow rates. Some portions of the coefficient curves that are used for data reduction appeared to be slightly changed. This implies possible damage and/or dirt accumulation on the probe head. In order to determine the effect of this change on the calculated tip clearance mass flow rate, the data for $t/c = 0.01981$ was reduced again using the new calibration curves and the calculated total mass flow rate appeared to be about 5% less than the one obtained using the first calibration curves. Since it is not known when the probe characteristics changed, all the three-hole probe data presented in this work are reduced with the first calibration curves and the difference quoted above represents an uncertainty on the tip clearance mass flow rate. This aspect is further discussed in section 7.1 where the chordwise mass flow rate distributions are compared. For reference, the recent calibration curves for the three-hole probe are included in Appendix K.

3.4.2.3 Pitch Angle Effect On The Accuracy of the Three-Hole Probe Measurements

Even though the probe measurements in the cascade were taken in flow regions in which the streamlines are expected to be nearly in the plane of the probe, the effect of pitch misalignment was also examined. Since this pitch angle check was done just before

the second calibration of the probe, the second calibration curves were used in the reduction of this data. For a number of pitch angles, the flow angles, dynamic and total pressures extracted from the probe pressures using the calibration curves are compared to the actual values in Figures 3.4.2.3.1 to 3.4.2.3.11. As can be seen from the flow angle plots in Figure 3.4.2.3.1, for pitch angles up to $\pm 30^\circ$ the inferred yaw angle is within $\pm 10^\circ$ of the actual value. In fact, in the yaw angle range $\pm 35^\circ$ this error is even smaller since the peak error value does not exceed $+4^\circ$. In order to ensure that for pitch angles smaller than $\pm 30^\circ$ the error in the measured flow angle follows the expected trend, tests were also performed at $\pm 10^\circ$ and $\pm 20^\circ$ pitch angles, but for clarity they are not included in Fig. 3.4.2.3.1. One extreme case with a pitch angle of -50° was considered (Fig. 3.4.2.3.2) for which the error in the measured flow angle still remains within $\pm 10^\circ$. These results indicate that even at high pitch angles the three-hole probe still enables yaw angle to be determined without excessive error.

From the dynamic pressure plots in Figures 3.4.2.3.3 to 3.4.2.3.8 it is seen that for pitch angles up to $\pm 10^\circ$ the maximum error in the measured dynamic pressure is only 6%, except in the -70° to -50° flow angle range where this error rises to 16%. In fact, even for larger pitch angles (up to 30°), within a yaw angle range of $\pm 20^\circ$, the error still remains below 6%. However, out of this yaw angle range the error increases rapidly with

Fig 3.4.2.3.1 THREE-HOLE PROBE YAW ANGLE MEASUREMENT

Fig. 3.4.2.3.2 THREE-HOLE PROBE YAW ANGLE MEASUREMENT
PITCH ANGLE = -50.0°

Fig. 3.4.2.3.3 THREE-HOLE PROBE DYNAMIC PRESSURE MEASUREMENT
PITCH ANGLE = -10.0°

Fig. 3.4.2.3.4 THREE-HOLE PROBE DYNAMIC PRESSURE MEASUREMENT
PITCH ANGLE = 10.0°

Fig. 3.4.2.3.5 THREE-HOLE PROBE DYNAMIC PRESSURE MEASUREMENT
PITCH ANGLE = -20.0°

Fig. 3.4.2.3.6 THREE-HOLE PROBE DYNAMIC PRESSURE MEASUREMENT
PITCH ANGLE = 20.0°

Fig. 3.4.2.3.7 THREE-HOLE PROBE DYNAMIC PRESSURE MEASUREMENT

PITCH ANGLE = -30.0°

O Actual

+ Measured

Fig. 3.4.2.3.8 THREE-HOLE PROBE DYNAMIC PRESSURE MEASUREMENT
PITCH ANGLE = 30.0°

increasing pitch angle and reaches magnitudes up to 40% for a pitch angle of $\pm 30^\circ$. Furthermore, as can be seen from the plot in Fig. 3.4.2.3.9, for the largest pitch angle considered (-50°) the error in the dynamic pressure is large for the whole yaw angle range examined and in some regions reaches magnitudes up to 60%.

The last parameter to be analyzed is the total pressure measured with the probe under nonzero pitch angles. The results are presented in the form of a total pressure "loss coefficient" where the reference total pressure is the actual stagnation pressure and the dynamic pressure used for nondimensionalizing is the actual local dynamic pressure. The results are given in Figures 3.4.2.3.10 and 3.4.2.3.11. As can be seen, for pitch angles up to $\pm 10^\circ$ the measured total pressure loss coefficient is a maximum of 0.05 which is only slightly higher than the basic uncertainty at zero pitch angle. The only exception is for yaw angles close to $\pm 70^\circ$ where the error is somewhat higher. At larger pitch angles the loss coefficient increases rapidly and at $\pm 30^\circ$ pitch angles the average loss coefficient is about -0.4. For the extreme case of -50° pitch angle, the average loss coefficient reaches an average magnitude as high as -1.0 which would certainly cause misleading analysis of a flow field. Before concluding the discussion on the measured total pressure, it is worth noting that according to the observations, at nonzero pitch angles the error in the measured dynamic pressure is mainly

Fig. 3.4.2.3.9 THREE-HOLE PROBE DYNAMIC PRESSURE MEASUREMENT
PITCH ANGLE = -50.0°

$\square$ Pitch Angle = 0.0°
 $\times$ Pitch Angle = 10.0°
 Δ Pitch Angle = 20.0°
 $\#$ Pitch Angle = 30.0°

Fig. 3.4.2.3.10 THREE-HOLE PROBE TOTAL PRESSURE MEASUREMENT

□ Pitch Angle = 0.0°
 X Pitch Angle = -10.0°
 Δ Pitch Angle = -20.0°
 # Pitch Angle = -30.0°
 + Pitch Angle = -50.0°

Fig. 3.4.2.3.11 THREE-HOLE PROBE TOTAL PRESSURE MEASUREMENT

on the plus side while the total pressure is under estimated which means that the error in the measured static pressures are even larger than the ones seen in the measured total pressures.

From these results one can see that for nonzero pitch angles the measured yaw angles are quite reliable. The measured dynamic pressures have relatively larger errors but are still usable. However, depending on the magnitude of the pitch angle, the total pressure measurements may give very misleading results. Therefore, the total pressure loss variation within the tip clearance will have to be treated with some caution.

As was noted at the beginning of this section, most of the three-hole probe measurements were taken in flow regions in which the streamlines are expected to be nearly in the plane of the probe. The only possible exception to this is the flow region within the separation bubble, a flow structure caused by the sharp turning at the blade tip pressure surface corner. Thus the above mentioned errors due to nonzero pitch angles might be present in the measurements within this region. It is worth noting that the flow field in the separation bubble is highly turbulent which will introduce an additional error to the measured total pressure: Goldstein (1936) noted that the total pressure measured by a pitot exceeds the actual value by an amount equal to the sum of the kinetic energies associated with the fluctuation velocities. Even though this type of an

investigation has not been performed for three-hole probes, the errors are likely to be the same order of magnitude as for pitot tubes. And this error, which is neglected in many practical cases, is presumably very small relative to the possible errors due to nonzero pitch angles, discussed earlier. In connection with the separation bubble it should also be noted that due to the shear flow the effective centre of the three-hole probe will be displaced. For pitot tubes investigation on this aspect has been done by Young & Maas (1936) and Macmillan (1954). In our case this is not very significant since, considering the possible errors due to nonzero pitch angles, the results of the measurements within the separation bubble are examined in a rather qualitative manner (see section 6.1.2). Finally, an additional error source for the three-hole probe measurements close to the endwall is the wall proximity. Studies on this aspect for circular and flattened pitot tubes have been performed by Macmillan (1956) and Ozarapoglu (1973). It is likely that the errors for the three-hole probe is the same order of magnitude as for the flattened pitot tubes. Thus, according to the correction given by Macmillan (1956), the effect of the wall proximity on the measured velocities close the endwall is less than 1%.

As of the beginning of this chapter, the term "flow angle" has been used for the yaw angle relative to the three-hole probe. For the remainder of the report the same term will represent the flow angle relative to the test section inlet velocity direction.

4. Experimental Technique and Test Section Inlet Flow Quality Measurements

4.1 Data Acquisition Technique

4.1.1 Data Acquisition System

For the largest tip clearance examined ($t/c = 0.03175$), a Taurus data acquisition board controlled by a micro computer was used as the data acquisition system. For the pressure readings the system input range was selected as ± 2.5 volts which, for the maximum available data acquisition resolution of 12 bits and a gain of 1, translated into an accuracy of ± 0.6 millivolts. With this data acquisition system a maximum sample rate of about 10 samples/second was achieved which was limited by the controller. For the other two clearances examined ($t/c = 0.02845$ and $t/c = 0.01981$), an HP 3497 scanner and an HP 3456 digital voltmeter, controlled by an IBM micro computer were used for data acquisition. The power line cycle integration time for the HP 3456 digital voltmeter (a factor providing an interrelationship between reading rate and accuracy) was set to 1 which, for the selected input range of ± 10 volts, gave results within $\pm 0.11\%$ of the actual value. Even though, compared to the Taurus board, the HP system enabled better electronic noise rejection and better compensation to temperature changes, there was not any gain in the sample rate since the system controller was still a

micro computer. With the HP system a sample rate of up to 45 samples/second, without any trade off in the accuracy quoted above, is possible by storing the data initially in the HP 3456 digital voltmeter. The memory is capable of storing up to 350 readings at a time. Thus the data can then be transferred to the computer memory in packages, which is faster than individual sample transfer. The disadvantage of this method is that if the total number of measurements taken during the sampling period is larger than 350, the package data transfer will cause interruptions within the sampling period. This is particularly important for the cases where some of the fluctuation periods in the pressure readings are larger than the time required for package data transfer (transferring 250 data points takes approximately 6 seconds). Therefore, even though this type of sampling option was built into the data acquisition programs, in order to be on the safe side, it was not used for the experiments discussed in this report.

For data acquisition, the pressures to be measured were converted into analog signals using Rosemount Model 831A3 variable capacitance differential pressure transducers with a range of ± 0.5 psid and a full scale output of ± 2.5 volts DC. For the three-hole probe measurements the contraction pressure difference was measured with a Setra Model 239 pressure transducer with a range of ± 0.5 psid and a full scale output of ± 2.5 volts DC. The transducers were calibrated using inclined

manometers or a transducer for which the calibration curve was already known; the calibration curves for all transducers used during experiments are given in Appendix D. The transducers were not recalibrated at the end of the experiments since comparison with the calibration results given by Amrud (1985) indicated that they are very stable.

The source code for the data acquisition programs, for both the Taurus board and the HP data acquisition system, are listed in Appendix E. The programs for the HP system require the analog input and thermal relay card options being used in the hardware while for the Taurus data acquisition programs the board has to be set to the input ranges and gains noted at the beginning of this section.

4.1.2 Data Sampling

The contraction pressure difference which, as will be discussed later, is used to determine the test section inlet dynamic pressure, was sampled together with the test section pressure data. However, both Taurus and HP data acquisition systems can sample only one quantity at a time. Therefore the test section data and the contraction pressure difference had to be sampled sequentially. In the cases where the result could be presented in nondimensional form, i.e., as a pressure coefficient, the data sampled throughout the sampling period were grouped so to form

measurement cycles consisting of "reference pressure - test section data - reference pressure". Then each test section pressure measurement was nondimensionalized using the average of the contraction pressure differences sampled in the same cycle. At the end of the sampling period these nondimensional samples were averaged. This method minimized the effects of the small amounts of drift in the wind tunnel operating point and was found to give good repeatability for the data.

The procedure for the three-hole probe measurements was slightly different since for data reduction purposes all three probe pressures were related to the same dynamic pressure. Therefore, all three probe pressures together with a contraction pressure difference sample were included in each measurement cycle. Furthermore, since for the three-hole probe measurements the results were in dimensional form, rather than relating the three probe data directly to the contraction pressure difference sampled in the same cycle, each dimensional quantity was averaged at the end of the sampling period.

Another issue related to data acquisition is the length of the sampling period. The pressure data were sampled long enough to obtain the long term average values. This period will depend not only on the type of pressure measured, but also on the type of flow in which the measurement is taken. Therefore, endwall static pressure, blade static pressure, free stream and boundary

each clearance size the endwall boundary layer at the test section inlet was traversed with a pitot probe, $2/3c$ upstream of the blade row. For these traverses a dial indicator was used which enabled a probe location accuracy of 0.025 mm and the alignment of the probe with the flow direction was obtained aerodynamically at the beginning of each traverse. For the three clearances the boundary layer velocity distributions, nondimensionalized by the inlet centerline velocity, are given in Fig. 4.3.2.1. The corresponding boundary layer parameters (displacement thickness, momentum thickness and the shape factor) are presented in Table 4.3.2.1 and the program used for their calculation is given in Appendix F. In order to determine these parameters, the boundary layer thickness had to be estimated which was somewhat ambiguous because of the nonuniformity of the test section inlet free stream flow. However, this is not very significant since those parameters are not very sensitive to small variations in the boundary layer thickness.

It is seen that the results for $t/c = 0.02845$ and 0.01981 are very similar. The increase in thickness which occurs for the larger clearance can be attributed to the extra diffusion. On the other hand, for $t/c = 0.03175$, the boundary layer is clearly much thinner. As mentioned earlier, this last data was obtained with the previous wind tunnel fan. It is thus evident that the new fan has resulted in a change in flow conditions at the cascade inlet. In order to confirm this reasoning, for the new

into the data acquisition program while for the three-hole and pitot probe measurements this period was compensated with the time spent for manual stepping of the probe.

4.2 Tunnel Operating Point

Since the inlet dynamic pressure was effected by the clearance size changes, it could not be used as a direct reference for the operating point and the contraction pressure difference at the exit of the settling chamber was used instead. For each tip clearance the dynamic pressure at the centerline, $2/3$ chord length upstream of the blade row, was determined as a fraction of the contraction pressure difference. It is worth noting that the value of this contraction factor was found to be a function of the position of the bleed ring at the outlet of the settling chamber (item 7 in Fig. 3.1.1). Thus the same bleed ring position should always be used; for the measurements reported here the bleed ring was kept closed.

The wind tunnel operating point is specified in terms of the Reynolds number based on the velocity at the test section inlet centerline, the blade chord, atmospheric pressure and settling chamber stagnation temperature. It was maintained constant at $4.3 \cdot 10^5 \pm 0.1 \cdot 10^5$ during all measurements except for some tests where the Reynolds number effects were investigated.

4.3 Test Section Inlet Flow

4.3.1 Turbulence Intensity

For the earlier fan, the test section inlet free stream turbulence intensity (u'/V_{CL}) was measured as 0.4% by Amrud (1985). After installing the new fan, the free stream turbulence intensity was measured again using a DISA type P11 normal hot wire and a 1050 series TSI constant-temperature anemometer. The root-mean-square of the fluctuating velocity component in the longitudinal direction, u' , was measured with a Bruel & Kjaer type 2425 RMS voltmeter. The DC output signal from this voltmeter was sampled together with the contraction pressure difference ($P_{sc1} - P_{sc2}$) using the HP data acquisition system. The resulting turbulence intensity, u'/V_{CL} , was determined to be 1.5% which is considerably higher than Amrud's (1985) result. The higher free stream turbulence will tend to energize the endwall boundary layer causing it to grow more rapidly. Therefore, it is likely to have thicker inlet endwall boundary layer with the new fan which, as is discussed in the next section, is in fact the case.

4.3.2 Inlet Flow Velocity Distribution

As was mentioned, the amount of diffusion before entering the blade row depended on the tip clearance size. Therefore, for

each clearance size the endwall boundary layer at the test section inlet was traversed with a pitot probe, $2/3c$ upstream of the blade row. For these traverses a dial indicator was used which enabled a probe location accuracy of 0.025 mm and the alignment of the probe with the flow direction was obtained aerodynamically at the beginning of each traverse. For the three clearances the boundary layer velocity distributions, nondimensionalized by the inlet centerline velocity, are given in Fig. 4.3.2.1. The corresponding boundary layer parameters (displacement thickness, momentum thickness and the shape factor) are presented in Table 4.3.2.1 and the program used for their calculation is given in Appendix F. In order to determine these parameters, the boundary layer thickness had to be estimated which was somewhat ambiguous because of the nonuniformity of the test section inlet free stream flow. However, this is not very significant since those parameters are not very sensitive to small variations in the boundary layer thickness.

It is seen that the results for $t/c = 0.02845$ and 0.01981 are very similar. The increase in thickness which occurs for the larger clearance can be attributed to the extra diffusion. On the other hand, for $t/c = 0.03175$, the boundary layer is clearly much thinner. As mentioned earlier, this last data was obtained with the previous wind tunnel fan. It is thus evident that the new fan has resulted in a change in flow conditions at the cascade inlet. In order to confirm this reasoning, for the new

○ $t/c = 0.03175$

+ $t/c = 0.02845$

□ $t/c = 0.01981$

Fig. 4.3.2.1 TEST SECTION INLET END WALL BOUNDARY LAYER

$Re = 4.3 \text{ E}05$

	δ^*/h	θ/h	H
$t/c = 0.03175$	0.00731	0.00544	1.344
$t/c = 0.02845$	0.03837	0.02519	1.523
$t/c = 0.01981$	0.02820	0.02049	1.377

Table 4.3.2.1 Inlet Endwall Boundary Layer Parameters
For All Three Clearances Examined
($Re = 4.3E05$)

fan, at zero tip clearance, 330 mm upstream of the blade row, detailed pitot tube traverses were performed at seven equally spaced stations distributed across the inlet section. In Figures 4.3.2.2 to 4.3.2.8, the resulting boundary layer velocity distributions are compared with those obtained by Amrud (1985). The corresponding boundary layer parameters together with the traverse locations are given in Table 4.3.2.2. It is evident that with the new fan the total pressure is considerably higher close to the bottom of the test section and somewhat lower close to the top.

4.4 Periodicity Studies

As was mentioned in section 3.2, flow periodicity in the blade passages was obtained by adjusting the side flaps and tailboards. The preliminary check on the periodicity was done using the backwall static pressure taps which are accurately located close to the leading edge on both suction and pressure surface sides of the blades. Adjustments were made until the passage pressure differences obtained from these taps were matched within 2.5% of the test section inlet centerline dynamic pressure. However, experiments indicated that the results obtained from the backwall static taps were very sensitive to the way the gap between the blade and the backwall was sealed. This is expected, since the contour that the sealing material follows is essentially the blade shape seen by the flow very close to the backwall.

Fig. 4.3.2.2. Velocity Profile At Test Section Inlet
Vertical Station #: 1

Fig. 4.3.2.3 Velocity Profile At Test Section Inlet
Vertical Station # : 2

Fig. 4.3.2.4 Velocity Profile At Test Section Inlet
Vertical Station # : 3

Fig. 4.3.2.5 Velocity Profile At Test Section Inlet
Vertical Station # : 4

Fig. 4.3.2.6 Velocity Profile At Test Section Inlet
 Vertical Station # : 5

Fig. 4.3.2.7 Velocity Profile At Test Section Inlet
Vertical Station # : 6

Fig. 4.3.2.8 Velocity Profile At Test Section Inlet
Vertical Station # : 7

Station #	Lateral Location (Y/W)	δ^*/h	θ/h	H
Bottom Side Wall	0.50			
1	0.36	0.0144	0.0102	1.410
2	0.24	0.0221	0.0172	1.285
3	0.12	0.0117	0.0084	1.402
4	0.0	0.0088	0.0061	1.448
5	-0.12	0.0143	0.0105	1.360
6	-0.24	0.0138	0.0099	1.400
7	-0.36	0.0137	0.0102	1.340
Top Side wall	-0.50			

Table 4.3.2.2 Inlet End Wall Boundary Layer Parameters
($Re = 4.3 \times 10^5$, $t/c = 0.0$)

3

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Therefore, the three-hole probe was traversed at blade midspan approximately 20 cm downstream of the blade row to obtain a more direct indication of the outlet flow periodicity. The results for all three tip clearances examined are presented in Figures 4.4.1 to 4.4.9. As mentioned, the readings were taken 20 cm downstream of the blade row. At this point the blade wakes have already diffused to some extent which makes them easier to measure. The disadvantage is that the flow angle information will be misleading if the top and bottom tailboards are set to considerably different angles. This was the case for $t/c = 0.03175$ where the difference between the tailboard angles is about 6° , causing the flow angle relative to the horizontal axis to decrease continuously from top to the bottom of the blade row. In that case another set of three-hole probe measurements was taken 13 mm downstream of the blades for which the flow angle distribution is presented in Fig. 4.4.10. Even though this figure is more difficult to analyze, the passage outlet portions of the distribution appear to be similar to each other indicating that the continuous flow angle change from top to the bottom flap, observed 20 cm downstream of the blade row, was indeed due to the difference between the tailboard angle settings.

The flow angle distributions for the other two clearances ($t/c = 0.01981$ and $t/c = 0.02845$) show that the second blade passage from the bottom of the test rig experiences a flow turning which is 2 to 2.5 degrees lower than the others. This

Fig. 4.4.1 Midspan Flow Angle Distribution Downstream
of the Blade Row ($t/c = 0.03175$)

Fig. 4.4.3 Midspan Total pressure Distribution Downstream
of the Blade Row ($t/c = 0.03175$)

Fig. 4.4.4 Midspan Flow Angle Distribution Downstream of the Blade Row ($t/c = 0.02845$)

Top of test section

Bottom of test section

Fig. 4.4.5 Midspan Velocity Distribution Downstream
of the Blade Row ($t/c = 0.02845$).

Top of test section

Bottom of test section

Fig. 4.4.7 Midspan Flow Angle Distribution Downstream
of the Blade Row ($t/c = 0.01981$)

Bottom of test section

Top of test section

Fig. 4.4.8 Midspan Velocity Distribution Downstream
of the Blade Row ($t/c = 0.01981$)

Bottom of test section

Top of test section

Fig. 4.4.9 Midspan Total pressure Distribution Downstream of the Blade Row ($t/c = 0.01981$)

Fig. 4.4.10 Midspan Flow Angle Distribution Downstream
of the Blade Row ($t/c = 0.03175$)

Bottom of test section

Top of test section

could not be avoided with different side flap and/or tailboard settings. The reason for this seems to be related to the excess total pressure observed in the flow at the bottom of the test section after the installation of the new fan (see section 4.3.2). The endwall oil visualization pictures for $t/c = 0.01981$ and $t/c' = 0.02845$ given in Figures 4.4.11 and 4.4.12 show that the centre blade tip experiences slightly lower pressure difference than other blades which ties into the fact that the passage underneath of that blade has a relatively low flow turning.

Nevertheless, as was mentioned above, for any of the clearances examined, the maximum difference between the passage flow turnings was 2.5 degrees. Furthermore, the minimum velocity magnitude in the blade wakes differed from one blade to another by a maximum of 5% of the inlet centerline velocity and the peak value of the total pressure loss coefficients differed by a maximum of 0.1 points. These results indicate that the periodicity obtained in the blade row was reasonably good.

Fig. 4.4.11 Endwall Surface Flow Visualization
($t/c = 0.01981$)

Fig. 4.4.12 Endwall Surface Flow Visualization
($t/c = 0.02845$)

5. Blade Surface and Endwall Static Pressure Measurements

5.1 Blade Surface Static Pressure Measurements

Even though in the work by Amrud (1985) detailed blade surface static pressure measurements were performed for an extensive number of tip clearance sizes, for completeness and because of the slight change in the blade incidence and in the spanwise location of the blade static pressure tap rows, the blade surface pressures were measured for all three clearances examined in this report. The results are given in Figures 5.1.1, 5.1.2 and 5.1.3. As can be seen from the results for row 1, other than the large peak which appears where the main tip leakage vortex starts to form, the smaller peaks due to the multiple vortices which could easily be seen in the work of Amrud (1985) are not very evident here. This is obviously due to the fact that the static pressure tap rows have been moved 2.3 mm from the tip after adding the interchangeable tips. On the plot for row 1 the blade suction peak can still be seen upstream of the peak due to the vortex. It is, however, smaller than the one observed at midspan because of the flow distortion towards the tip of the blade. When moving towards midspan, the peak due to the tip leakage vortex shifts downstream which is a result of the conical shape of the vortex.

Amrud (1985) stated that the peak due to the tip leakage vortex increases in magnitude and shifts downstream with

Fig. 5.1.1 BLADE SURFACE C_p DISTRIBUTION
 ($t/c = 0.03175$ $Re = 4.3E05$)

Fig. 5.1.2 BLADE SURFACE C_p DISTRIBUTION
($t/c = 0.02845$ $Re = 4.3E05$)

increasing clearance size. As was discussed in Chapter 2, these trends have also been observed by a number of other investigators. However, from the plots for row 1 given in Fig. 5.1.4 it is seen that the peak magnitude for $t/c = 0.02845$ is slightly smaller than it is for $t/c = 0.01981$. In order to clarify this point, the results obtained by Amrud (1985) are reproduced in Fig. 5.1.5. In this figure, if the results for the clearances that are close to the ones examined in this report ($t/c = 0.0222$ and 0.0286) are compared to each other, the magnitude of the vortex peak seen on row 1 decreases slightly with increasing clearance size which is in fact the opposite of the trend that is observed from the other clearances on the same figure. This indicates that the recent results do not contradict the ones presented by Amrud (1985), rather, both the recent results and the measurements presented by Amrud show that the trend in the peak size is not very distinct for clearance sizes above 2%. Furthermore, from Fig. 5.1.5 it is seen that the rate of increase of the peak value decreases with increasing clearance size. This suggests that the peak observed for $t/c = 0.03175$, which is considerably higher than the ones for $t/c = 0.02845$ and 0.01981 , may be affected by some of the changes in the inlet flow conditions which were discussed in section 4.3. In other words, if that clearance size were examined with the new fan as the wind source, it is possible that the peak magnitude at row 1 would be closer to the one for $t/c = 0.02845$. As was noted in the previous paragraph, Amrud (1985) and a number of other

Fig. 5.1.4 BLADE SURFACE C_p DISTRIBUTION [ROW 1]
($Re = 4.3E05$)

Fig. 5.1.5 Blade Surface C_p Distribution (Row 1)
(reproduced from Amrud (1985))

investigators observed a rearward shift in the chordwise location of the peak. In the recent results, this trend is not very clear. This is again explained by the fact that for the clearance range examined herein, this shift is not very distinct which is also evident from Amrud's results.

For clarity, the blade static pressure measurements other than for rows 1,2,3,4 and 14 were not given in Figures 5.1.1, 5.1.2 and 5.1.3. For reference they are included in Appendix L.

5.2 Endwall Static Pressure Measurements

As was discussed earlier, a portion of the plexiglass endwall is instrumented with a grid of static pressure taps. Even though the grid was located so as to obtain detailed measurements in the region close to the blade tip, the taps are distributed so that using the fact that the flow in the blade passages are periodic, it was possible to obtain a grid of endwall static pressure measurements corresponding to a complete blade passage. In fact, this advantage was used to produce the endwall static pressure contour plots which are discussed later in this section. The taps are essentially located so to form a grid consisting of 15×15 mm² squares. The increased grid intensity close to the tip clearance region (7.5×7.5 mm²) enabled the accurate measurement of the endwall static pressure distribution which includes local peaks in that region. Figure 3.2.2 shows the tap

locations relative to the blade.

As was noted in section 2.10.1, Lakshminarayana & Horlock (1962) introduced a "retained lift" concept at the blade tip which they use for determining the amount of vorticity shed of the blade tip. They determine the value of this retained lift by extrapolating the spanwise lift distribution curves to the blade tip. In section 2.11 it was noted that following these authors, Lewis & Yeung (1977) obtained this retained lift from static pressure measurements on the endwall along a contour following the blade shape. Their results showed reasonable agreement with Lakshminarayana & Horlock's (1962) values. Considering Lewis & Yeung's (1977) procedure, it appears that the retained lift might be related to the pressure difference that drives the tip clearance flow close to the endwall (for the rest of the text this will be referred to as the "endwall driving pressure difference"). In order to clarify this point, following Lewis & Yeung's procedure, the endwall static pressure values for $t/c = 0.03175$ were determined along a contour following the blade shape, by interpolation from the endwall static pressure measurements. The results are plotted in Fig. 5.2.1 together with the corresponding midspan blade surface pressure distribution. The scatter in the interpolated endwall pressures is probably due to the fact that many of the points fell in regions of rapidly varying pressure which made it difficult to obtain accurate interpolated values. The area between the

Fig. 5.2.1 END WALL AND BLADE MIDSPAN STATIC PRESSURE DISTRIBUTION

($t/c = 0.03175$ $Re = 4.3 \text{ E}05$)

suction and pressure surface curves essentially defines the lift developed at that spanwise location. If the interpolated endwall static pressures are analyzed in this manner, one can see that the lift retained at the endwall is very small compared to the lift developed at midspan with, in fact, the pressure difference briefly changing its sign within a region close to the leading edge. If these results were presented in the form of a retained lift coefficient (C_{LR}/C_{L2D}), a reasonable agreement with Lakshminarayana & Horlock's (1962) and Lewis & Yeung's (1977) results, given in Fig. 2.11.5 would be obtained.

In the procedure described above, the endwall driving pressure difference was calculated from the endwall pressures interpolated along the projection of the blade surface contour. This would be an appropriate approach if the endwall peak pressures that drive the tip leakage flow close to the endwall had fallen on this contour. However, from the endwall static pressure contour plots for all three clearances, presented in Figures 5.2.2, 5.2.3 and 5.2.4, one can see that the pressure minimum location is shifted into the gap while the pressure maximum location appears to be moved away from the pressure surface edge into the passage. Therefore, as is clarified in the next paragraph, determining the endwall driving pressure difference with the procedure described above will give very misleading results.

Following the observation noted in the previous paragraph,

Fig. 5.2.2 Endwall C_p Distribution
($t/c = 0.03175$ $Re = 4.3E05$)

Fig. 5.2.3 Endwall C_p Distribution
($t/c = 0.02845$ $Re = 4.3E05$)

Fig. 5.2.4 Endwall C_p Distribution
($t/c = 0.01981$ $Re = 4.3E05$)

instead of interpolating along the blade surface contour, the results obtained from the endwall static pressure tap grid were analyzed along lines aligned at 45° to the horizontal test rig axis (Fig. 5.2.5), which is the approximate flow direction through the tip gap for this particular cascade. For $t/c = 0.03175$ the endwall driving pressure difference, which was taken as the maximum pressure difference along the particular line, was determined along those lines and is plotted in Fig. 5.2.6. On the plot the x co-ordinate for each pressure difference is the point where the line on which this difference was calculated crosses the blade meanline. As can be seen, this time the magnitude of the endwall driving pressure difference is comparable to the midspan pressure differences determined along lines normal to blade chord.

The endwall pressures for the other two clearances were analyzed in the same way as discussed above and the results are plotted in Fig. 5.2.7. It is seen that for all three clearances the endwall driving pressure is very similar to the blade pressure difference at midspan. In the leakage models introduced in section 7.2, used for ideal tip clearance mass flow rate calculation, a pressure difference easy to determine by the designer and representing the pressure difference that drives the tip clearance flow will be needed. From the results in Fig. 5.2.7 it is clear that the blade pressure difference at midspan, i.e., the undisturbed pressure distribution, is very suitable for

Fig. 5.2.5 Endwall Static Pressure Taps and the Lines Along Which the Endwall Driving Pressure Difference Is Calculated

Fig. 5.2.6 DRIVING PRESSURE DIFFERENCE DISTRIBUTION

($t/c = 0.03175$ $Re = 4.3E05$)

Fig. 5.2.7 DRIVING PRESSURE DIFFERENCE DISTRIBUTION ($Re = 4.3E05$)

this purpose.

The further examination of the plots in Fig. 5.2.7 shows that while the endwall driving pressure difference curve follows essentially the same trend as the curve obtained from midspan, it is shifted downstream by about 25% of the chord length. This can be explained with the axial momentum of the flow through the tip gap.

In addition to the observations discussed above, there are a number of other conclusions that can be drawn from the endwall static pressure contours. First of all, with decreasing clearance size the pressure maximum location shifts closer to the pressure surface edge of the blade. This is to be expected since decreasing the clearance size reduces the leakage through the gap causing the dividing stream line on the endwall to move closer to the blade, which is also seen on the flow visualization pictures. Furthermore, the suction peak location does not shift axially for the clearance sizes considered. This is consistent with the lack of shift of the suction peak at the blade tip noted in section 5.1. Finally, the contour plots also indicate the direction of the tip leakage vortex core relative to the blade row inlet flow direction. This information can be used for determining the accuracy of various expressions used in the literature for predicting the leakage vortex direction.

6. Three-hole Probe Measurements Within The Tip Clearance

6.1 Measurements Along The Blade Meanline

Extensive three-hole probe measurements were performed in the tip clearance giving a detailed velocity magnitude, flow angle and total pressure distribution. The traverses across the gap were performed at 37 chordwise stations located as shown in Fig. 6.1.1. The measurement stations were located along the meanline, since that is where the velocity vector is expected to be most nearly parallel to the endwall and therefore in the plane of the three-hole probe. For the first half of the chord length the stations are closely spaced (with an interval of 2% chord length), while towards the trailing edge the spacing between the stations is doubled since the velocity magnitude and flow angle change more gradually in that region. At each chordwise station the three-hole probe was traversed across the gap with a step size of 0.508 mm. This step size is accurate within 0.025 mm as determined by the resolution of the dial indicator mounted on the traversing gear.

6.1.1 Velocity Magnitude and Flow Angle Distribution

The local magnitudes of velocity and flow angle were two of the quantities obtained from the three probe pressures. For convenience they are presented together in the form of velocity

Fig. 6.1.1 Three-hole Probe Traverse Locations

vectors in Figures 6.1.1.1, 6.1.1.2 and 6.1.1.3. The velocity is nondimensionalized by the test section inlet centerline velocity. In these figures the distance between subsequent measurement planes is simply the measurement step size across the gap. For the largest two clearances it was not possible to obtain measurements very close to the endwall due to limitations with the traversing gear. For those cases this was not an important problem since the region that could not be traversed was only a small percentage of the gap height. However, this percentage would become significant for the smallest clearance case. Therefore, some temporary modifications had to be made to the traversing gear to enable measurements closer to the endwall. The number of measurement stations across the gap varied from 10 to 14, depending on the clearance.

As can be seen from the velocity distribution plots, close to the blade tip the flow behaviour is significantly different from the regions close to the endwall. This is expected since the sharp turning at the pressure surface edge of the blade forces the flow to produce a separation bubble. However, near the leading edge, within a region of about 20% chord length, even very close to the blade tip the velocity magnitude and directions are very similar over the whole of the gap. This suggests that in this region the separation bubble is small and does not extend to the centerline where the three-hole probe measurements were taken. Other than in this region, the presence of the separation

BLADE TIP

200

4.4 $2/t$ (%)

30

10.8

36.4

17.2

42.8

23.6

49.2

SEE OVER

Fig. 6.1.1.1 Tip Gap Velocity and Flow Angle Distribution Along the Blade Meanline ($t/c = 0.03175$)

4.9 $\frac{P}{t}(\%)$

33.5

12.1

40.6

19.2

47.8

26.3

54.9

SEE OVER

Fig. 6.1.1.2 Tip Gap Velocity and Flow Angle Distribution Along the Blade Meanline ($t/c = 0.02845$)

BLADE TIP

204

7 1/4 (%)

18.1

17.3

58.4

27.6

68.6

37.8

78.9

SEE OVER

Fig. 6-1.1.3 Tip Gap Velocity and Flow Angle
Distribution Along the Blade Meanline
($t/c = 0.01981$)

bubble is observed along the blade centerline showing that the separation bubble has grown to a larger size. In order to obtain more detailed information about the separation bubble size, the three hole probe was traversed also along lines extending from the pressure surface edge to the suction surface. The results for this will be discussed in section 6.2.

Out of the separation bubble the velocity vectors follow a smooth trend from leading to trailing edge. An interesting result is that the velocity magnitude does not drop towards the endwall. On the contrary, the maximum velocity magnitudes were observed in the measurement plane closest to the endwall. Since out of the separation bubble the change in the flow direction across the gap is very small, the component of velocity normal to the blade chord line follows a similar trend to the resultant velocity. This result is consistent with the observations concerning the large driving pressure difference still present near the endwall, as discussed in the previous chapter. Furthermore, if the measurement planes closest to endwall for all three clearances are compared, one can see that both the velocity magnitude and flow direction distributions are very similar for the three clearances, which is again consistent with the endwall driving pressure differences compared in Fig. 5.2.7.

6.1.2 Total Pressure Distribution

Another parameter that was extracted from the three-hole probe data was the total pressure. The resulting total pressure loss coefficient distributions are presented as contour plots in Figures 6.1.2.1, 6.1.2.2 and 6.1.2.3. The reference total pressure and the dynamic pressure used for forming the total pressure loss coefficient are the ones at the test section inlet centerline. Note that, using the inlet total pressure in this loss coefficient implies that the distribution seen in the contour plots also includes the losses that occur until the flow reaches the gap entrance. Nevertheless, from the loss distribution out of the separation bubble it is observed that those losses which occur before the flow reaches the gap entrance are negligible.

As was discussed in section 3.4.2.3, under large pitch angles the probe may give misleading total pressure measurements. Since the effect of pitch angle on the measured yaw angles is relatively small, it seems more appropriate to consider the velocity vector distribution rather than the total pressure when the flow associated with the separation bubble is analyzed. However, since it is easier to determine and compare the size of the separation bubble on a contour plot of the total pressure loss distribution, it is worth investigating the reliability of this approach. As noted in section 4.2, for pitch angles up to

Fig. 6.1.2.1 Tip Clearance Total Pressure Loss Coefficient Distribution ($t/c = 0.03175$, $Re = 4.3 \times 10^5$)

Fig. 6.1.2.2 Tip Clearance Total Pressure Loss Coefficient Distribution ($t/c = 0.02845$, $Re = 4.3 \cdot 10^5$)

Fig. 6.1.2.3 Tip Clearance Total Pressure Loss Coefficient
Distribution ($t/c = 0.01981$, $Re = 4.3 \cdot 10^5$)

$\pm 10^\circ$ the error in the measured total pressure, as a total pressure coefficient, is ± 0.05 points. Also, along the blade meanline the tip clearance flow out of the separation bubble is very close to being parallel to the endwall and the pitch angle is unlikely to be more than $\pm 10^\circ$. Therefore, based on the total pressure loss distribution along the meanline, the edge of the flow region with high losses (i.e., the separation bubble) can be determined with good accuracy and this fact will be used in the following discussion.

Another issue is the reliability of the measured total pressure losses within the separation bubble. According to the results that will be presented in the next section, for most of the chord length, the bubble covers a major portion of the blade thickness. Therefore, the values obtained at the blade centerline are roughly from the centre of the bubble where the radial velocity component is small. This implies that the error in those measured peak values should not be very high. Nevertheless, the total pressure loss distribution within the bubble should be treated with caution and the possibility of errors, of the magnitudes noted in section 3.4.2.3, should be kept in mind.

As can be seen from the contour plots, along the blade mean line at chordwise stations where the bubble is observed, it covers about 30 to 40% of the gap height. The most severe losses in the separation bubble occur in the region where the pressure

difference across the gap reaches its peak value. This is an expected result since the large magnitude of the velocity across the gap causes very high tangential velocity gradients within the separation bubble resulting in high shear stress. As observed from the velocity plots, close to the leading edge the separation bubble is small. The chordwise location where the separation bubble rapidly starts to grow can be seen clearly on the total pressure contour plots. If this location is compared to the location of the tip clearance vortex peak observed on the row 1 blade surface pressure distribution, they appear to be very close to each other, indicating an interaction between the formation of the tip clearance vortex and the separation bubble phenomenon. As noted, the separation bubble covers roughly 30% to 40% of the gap height. Relative to the gap height, the $t/c = 0.02845$ case appears to have the largest separation bubble size while for the other two clearances the bubble size relative to the gap height is very similar at all chordwise locations. The velocity vector plots lead to the same conclusion. Intuitively, the relative bubble size should follow a certain trend with gap size. Since when the gap height is decreased the aspect ratio of the gap reduces, the bubble size relative to the gap height is expected to drop. This is in fact the observed trend when the $t/c = 0.02845$ and 0.01981 cases are compared. However, the largest clearance ($t/c = 0.03175$) does not follow this trend. This is presumably caused by the fact that this clearance is examined under different inlet flow conditions which implies that

comparison of this clearance case to the other ones will include the effects of other parameters.

In the tip clearance region close to the endwall the total pressure loss is zero or very close to zero except in the region near the leading edge. This indicates that the fluid passing through the tip gap is essentially free stream fluid. This is also supported by the smoke visualization studies presented by Amrud (1985): the smoke inserted into the endwall boundary layer at the test section inlet indicated that only a small portion of the tip gap flow close to the leading edge includes inlet boundary layer fluid. This result, i.e., the fact that the tip leakage flow consists of free stream fluid is consistent with the secondary flow behaviour: as is known, after entering the blade passage, the low energy endwall boundary layer fluid forms the so called passage vortex. As a result of the pressure gradient, this vortex is shifted towards the suction side of the passage, i.e., away from the entrance of the tip gap. Therefore, it is likely that this low energy fluid will not contribute to the tip leakage flow, which explains the above noted observations.

Another way of presenting the total pressure data is to consider the mass averaged total pressure loss coefficient distribution which is given for three clearances in Figures 6.1.2.4, 6.1.2.5 and 6.1.2.6. For all three cases the mass

$$t/c = 0.03175$$

$$Re = 4.3E05$$

Fig. 6.1.2.4 Tip Clearance Mass Averaged Total Pressure Loss Coefficient Distribution

Fig. 6.1.2.5 Tip Clearance Mass Averaged Total Pressure Loss Coefficient Distribution

$t/c = 0.01981$

$Re = 4.3E05$

Fig. 6.1.2.6 Tip Clearance Mass Averaged Total Pressure Loss Coefficient Distribution

averaged loss coefficient distribution along most of the chord length is on the order of -0.5 . Since the mass flow rate associated with the bubble flow contributes very little to the total flow through the gap, even though the losses within the separation bubble are high, the region out of the separation bubble, with very small losses and high mass flow rate, prevents the mass averaged loss distribution curves from rising to a high level. The only exception is at the chordwise location where the driving pressure difference through the gap reaches its peak value. At this location, the losses within the bubble are very large, causing the mass averaged loss distribution curves to rise.

6.2 Three-Hole Probe Traverses From the Pressure Surface To the Suction Surface Corner of the Tip Clearance

As was mentioned in section 6.1.1, for tip clearances $t/c = 0.01981$ and 0.02845 some three-hole probe measurements were also performed at stations other than along the blade centerline. In order to obtain the complete cross sectional picture of the gap flow, these additional traverse stations were located so to form measurement planes normal to the blade centerline. 5 measurement planes were examined and these planes were distributed along the blade chord so to obtain information from different sections of the gap. For convenience these planes will be numbered starting from the leading edge and will be referred

to with these numbers for the remainder of this section. The velocity magnitude and the flow angle distributions obtained from these measurements are presented in Figures 6.2.1 and 6.2.2 in the form of velocity vectors, with the velocity nondimensionalized as usual by the inlet centerline velocity. In the measurement planes close to the blade tip, in some regions the results are slightly scattered which undoubtedly is due to increased measurement errors within the separation bubble.

As is observed from the plots, in planes 1 and 2 the separation bubble covers only a small portion of the blade thickness and is located close to the pressure surface edge allowing the flow to reattach to the blade tip. This ties into the fact that in this region the bubble was not observed from the measurements along the centerline. At locations 3, 4 and 5, due to the reduced blade thickness and significantly increased bubble size, the separation bubble covers almost the whole blade thickness. Depending on the clearance size, the third and fourth measurement planes from the blade tip are the last planes where the separation bubble is visible. In these planes the only location where the separation bubble can be observed is plane 3 indicating the chordwise location where the bubble size reaches its largest value. As a matter of fact, at this point it is possible to state that the structure seen on the blade tip is somewhat different from an ordinary separation bubble. Looking at the velocity vector distribution within the bubble, there is clearly an axial

SEE OVER

SEE OVER

Fig. 6.2.1 · Tip Clearance Velocity and Flow Angle Distribution In Planes normal to Blade Meanline ($t/c = 0.02845$)

SEE OVER

SEE OVER

velocity component, which was also observed by Bindon (1987), and the flow angle distribution across the bubble shows a smooth trend which is more like the flow picture seen in a vortex. Therefore, it is more appropriate to refer to this phenomenon as a small scale vortex structure rather than a separation bubble.

Outside the "separation bubble", within each of the 5 planes the velocity vectors are very similar in both magnitude and direction. The only exception is in the region which appears to be above the separation bubble where the bubble size reaches its peak value. In this region the velocity turns towards the direction normal to the chord line and slightly increases in magnitude. This can be explained by the fact that the stream tube passing through the gap converges over the separation bubble, which by conservation of mass causes the flow to accelerate.

The flow region close to endwall, right at the gap entrance, is unlikely to be effected by this converging-diverging effect. Furthermore, close to the exit of the gap, after passing over the separation bubble, the stream tube again extends to the whole gap size. Therefore it is possible to compare the direction and magnitude of the velocity vector at gap entrance and exit without considering the effect of the separation bubble. This comparison indicates that the flow has already been accelerated before entering the tip clearance. This is consistent with the point of

maximum endwall pressure lying in the blade passage some distance from the tip gap entrance, as noted in section 5.2. This observation will be used in section 7.2 to calculate the ideal mass flow rate through the tip gap.

7. Mass Flow Rate Associated With the Tip Clearance Flow

7.1 Calculation of the Actual Mass Flow Rate Through the Tip Clearance

The detailed three-hole probe measurements performed in the tip gap along the blade centerline enabled an accurate calculation of the mass flow rate through the gap.

As discussed in section 6.1, the velocity magnitudes measured at the points within the separation bubble are not very reliable. However, the velocity magnitudes obtained in that region are small and the flow directions are close to the chordwise direction so that the contribution to the total mass flow rate through the tip clearance is also small. The separation bubble essentially blocks part of the tip clearance.

The closely spaced measurement grid made it reasonable to assume linear variations in velocity between measurement points. For a measurement point where the flow angle seen by the probe was out of the calibrated range, the velocity normal to the chord line was interpolated from the results at points on each side of this point. The program used for the mass flow rate calculation is given in Appendix G.

In order to ease the comparison of the tip clearance mass flow

rate distribution for different clearance sizes, the mass flow rate is considered in a nondimensional form,

$$(\dot{m}_{\text{gap}}/A)/(\dot{m}_{\text{psg}}/A_{\text{psg}})$$

where $\dot{m}_{\text{gap}}/A$ is the total tip gap mass flow rate per unit gap area (the area is projected on to the blade chord) and $\dot{m}_{\text{psg}}/A_{\text{psg}}$ is the passage inlet mass flow rate per unit passage inlet area. For the remainder of the text, this parameter will be referred to as $\dot{m}_{c1}$. Note that, neglecting density changes, $\dot{m}_{c1}$ is in effect the ratio of the velocity normal to chord line to the undisturbed passage inlet velocity.

$\dot{m}_{c1}$ was calculated for all three clearances and the results are as follows :

$t/c = 0.03175$	$\dot{m}_{c1} = 0.882$
$t/c = 0.02845$	$\dot{m}_{c1} = 0.802$
$t/c = 0.01981$	$\dot{m}_{c1} = 1.016$

Comparing these results shows that when the clearance size is changed from $t/c = 0.02845$ to 0.01981 the percentage reduction in the mass flow rate is less than the percentage reduction in the clearance size. In section 5.2 it was observed that the driving pressure difference through the gap is essentially the same for all three clearances. Furthermore, if Rains' (1954) analysis is

used to determine which forces are dominant in driving the tip leakage flow, it is found that even for the smallest clearance examined, the viscous effects are negligible and the inertia forces are dominant. Thus the most likely explanation for the trend noted above is the fact that, as was discussed in section 6.1.2, the bubble size relative to the gap height decreases when the clearance size is reduced from $t/c = 0.02845$ to 0.01981 .

If the chordwise distribution of the tip clearance mass flow rate is considered for these two clearance cases (Fig. 7.1.1), it is observed that the above indicated trend holds at all chordwise locations. This implies that at all chordwise locations the relative bubble size for $t/c = 0.02845$ should be larger than for $t/c = 0.01981$, which is consistent with the results obtained from the total pressure contour plots in section 6.1.2

The total tip clearance mass flow rate for $t/c = 0.03175$ does not precisely follow the trend noted above, although it is similar to that for $t/c = 0.02845$. The discrepancy does not appear to be due to the change in the three-hole probe calibration characteristics (as was noted in section 3.4.2.2, the calibration change caused a 5% uncertainty in the clearance mass flow rate). When the chordwise mass flow rate distributions for $t/c = 0.01981$, based on the original and revised calibration curves, are compared, almost all of the 5% change appears in a region extending from $0.55c$ to $0.75c$. On the other hand,

Fig. 7.1.1 Tip Clearance Mass Flow Rate Distribution
($Re = 4.3E05$)

comparison of the chordwise mass flow rate distributions for $t/c = 0.03175$ and 0.02845 (Fig. 7.1.2) indicates that the difference in mass flow rates is seen at all chordwise locations. Therefore, it seems likely that the apparent discrepancy is the result of the difference in the inlet flow conditions for the two large clearance cases (see section 4.3), rather than the calibration change. However, since there are too many parameters that are changed at the same time (inlet boundary layer thickness, free stream turbulence level and clearance size), it is not possible to determine their individual effects. Therefore, the $t/c = 0.02845$ and 0.01981 cases, for which the clearance size was the only parameter that was changed, should be used for determining the trend, which has already been done in the previous paragraph.

As was noted in section 6.1.2, the total pressure loss coefficient distribution in the clearance and Amrud's (1985) smoke visualization studies indicated that the tip clearance flow largely consists of free stream fluid. In this connection it is worth comparing the mass flow rate associated with the endwall boundary layer at test section inlet to the tip clearance mass flow rate. Since the flow at the test section inlet was not very uniform, the location of the endwall boundary layer edge was somewhat ambiguous (see Fig. 4.3.2.1). On the other hand, the experimental momentum thicknesses, θ , and shape factors, H , are not ambiguous. Thompson (1965) proposed a family of two

Fig. 7.1.2 Tip Clearance Mass Flow Rate Distribution
(Re = 4.3E05)

parameter velocity profiles for turbulent boundary layers on smooth surfaces. For given values of θ and H , a Thompson profile can be constructed and it has been shown to be a good fit to the experimental velocity distribution. Therefore, Thompson profiles were fitted to the endwall boundary layer profiles and the resultant boundary layer thicknesses were used in place of the ambiguous experimental values. For the three clearances the ratio of the mass flow rate through the tip gap ($\dot{m}_{\text{gap}}$) to the mass flow rate associated with the inlet endwall boundary layer of one passage height ($\dot{m}_{\text{bnd}}$) is as follows:

$$\dot{m}_{\text{gap}}/\dot{m}_{\text{bnd}}$$

$$t/c = 0.03175 : 0.726$$

$$t/c = 0.02845 : 0.273$$

$$t/c = 0.01981 : 0.205$$

It is seen that for all three cases the mass flow rate associated with the endwall boundary layer at the blade row entrance is either comparable to or larger than the tip clearance total mass flow rate. It is therefore interesting that, despite of the relatively large mass of the endwall boundary layer fluid, virtually no endwall boundary layer was observed inside the tip gap. This indicates that for clearance sizes seen in practice, even if the mass flow rate associated with the inlet boundary layer is substantially larger than the total tip leakage

flow rate, almost all of the endwall boundary layer does not enter the tip gap but remains in the passage. As was discussed in section 6.1.2, this type of behaviour is explained by the fact that once the low energy fluid has entered the gap, due to the presence of large pressure gradient, it is shifted towards the suction side of the passage, i.e, away from the tip gap entrance.

7.2 Calculation of the Ideal Mass Flow Rate Through the Tip Clearance & Discharge coefficient

As was noted in Chapter 2, tip clearance studies reported in the literature have been mainly oriented towards the effect of the tip clearance on efficiency. Therefore, most of the investigators have focused on tip clearance loss correlations rather than precise tip leakage flow models. Undoubtedly, in all of the loss correlations, either implicitly or explicitly, the leakage flow has to be modeled. However, since in those studies flow modeling is not the main objective, instead of the agreement of the model with the real leakage flow, the accuracy of the predicted losses has been used as the criterion for the degree of success. Even though some loss correlations appear to be quite successful, this does not necessarily mean that the success is a result of accurate flow modeling.

7.2.1 The Leakage Model of Booth et al.

It appears that the most extensive work on leakage modeling is that reported by Booth et al. (1982) who, on the basis of Rains' (1954) analysis and their own experimental observations, introduced a prediction scheme for determining the velocity and flow angle distribution in the tip clearance. As a starting point, it was decided to compare their model predictions with the present experimental results. The model can be summarized as follows :

- (a) Select a point on blade pressure surface edge;
- (b) Determine the static pressure at this point from experiment or from a blade-to-blade calculation procedure;
- (c) Assume a magnitude for the velocity component normal to the centerline; this together with the tangential velocity on the blade pressure surface determined at this point will give a flow direction;
- (d) Under the assumption of a straight stream line through the tip gap determine the point at which the streamline crosses the suction surface;
- (e) Determine the static pressure at this crossing point, again from experiment or theoretical calculation. Apply a modified Bernoulli equation which includes a discharge coefficient (equation 7.2.1.1) along this stream line to determine the

magnitude of the normal velocity component. If this value does not agree with that assumed in step (c) or obtained in the previous iteration, steps (d) and (e) are repeated. This is continued until the normal velocity magnitude has converged. The process is repeated for a series of points along the blade to define the flow through the gap.

$$V_N = C_D \left(\frac{2(P_1 - P_2)}{\rho} \right)^{\frac{1}{2}} \quad (7.2.1.1)$$

The assumptions used in this model can be summarized as follows:

- (i) The tip clearance flow is driven by the pressure difference across the gap (i.e., viscous effects other than the separation bubble is not taken into account).
- (ii) Tangential momentum is conserved across the gap.
- (iii) The stream line across the tip gap is assumed to be straight.
- (iv) The fluid entering the tip clearance consists of free stream fluid only.

Assumption (i) was first made by Rains (1954). From his analysis (see section 2.10) he concludes that for clearance sizes used in practice the inertia forces are dominant. To some extent

this is also confirmed theoretically by Booth et al. (1982).

The second assumption was again first made by Rains and is based on the fact that the pressure gradient across the gap is much larger than the one along the blade. The experimental results of Booth et al. (1982) (see section 2.12) confirm this assumption to some extent. The three-hole probe measurements taken along lines extending from the gap entrance to the gap exit, presented in section 6.2, showed that the flow accelerates before entering the gap which, under ideal conditions, implies that the normal velocity remains unchanged through the gap. From those measurements it was also seen that there is not a visible difference between the flow directions at gap entrance and exit. Therefore, the conservation of the tangential momentum across the clearance is also supported by the present observations.

The third assumption that the stream lines through the tip gap are straight was confirmed by Booth et al. (1982) who observed the traces of dye clusters injected into the flow (see section 2.12). From the present observations noted above it was concluded that both the normal and tangential velocities remain the same across the gap which then confirms the straight stream line assumption.

7.2.2. Criticism of the Leakage Model of Booth et al. and the Introduction of Improved Models

As was noted in the previous section, the apparent assumptions built into the leakage model of Booth et al. (1982) are reasonable. On the other hand, there are a number of aspects associated with this model that are open to criticism. These are discussed in the following paragraphs.

First of all, as was discussed, the acceleration is completed before the flow enters the gap. While this point has been very useful in confirming the assumptions noted above, it makes it difficult to justify the usage of the pressure difference along the streamline (along AB in Figure 7.2.2.1) for calculating the magnitude of the velocity component normal to the chord. Since the acceleration is completed before entering the gap, the normal velocity calculation should rather be based on the pressure difference along AC in Figure 7.2.2.1. Considering the fact that the velocity component normal to the chord is substantially larger than V_T , the chordwise movement during acceleration is expected to be very small. Thus, it is reasonable to approximate AC with AD. In fact, the leakage velocity used in Rains' (1954) loss correlation is calculated on this basis. This will also greatly simplify the leakage model of Booth et al. (1982) since an iterative procedure for determining the normal velocity will no longer be necessary. For the remainder of this

Fig. 7.2.2.1 Calculation Of the Velocity Component Normal To the Blade Meanline

section the leakage model that includes this modification will be called the "Simple Model" while the model suggested by Booth et al. (1982) will be referred to as "Booth's Model".

Secondly, as is seen from equation 7.2.1.1, the discharge coefficient is built into this equation, reducing the magnitude of the velocity component normal to the chord (V_N). As was discussed in the previous paragraphs, the idealized flow assumptions are confirmed in the gap region out of the separation bubble and endwall boundary layer. Therefore, in this region the magnitude of V_N obtained by applying Bernoulli's equation (without a built in discharge coefficient) is expected to be reasonable. The discharge coefficient then accounts for the lower V_N in the endwall boundary layer and within the separation bubble. The transition from ideal to actual flow with this type of conventional use of the discharge coefficient is shown schematically in Fig. 7.2.2.2. Booth's Model uses a somewhat different approach. Using equation 7.2.2.1 for calculating V_N implies that across the whole gap height (i.e., including the region out of the separation bubble and endwall boundary layer where the ideal flow assumptions are valid) V_N is lower than the one that would have been obtained from Bernoulli's equation (see Fig. 7.2.2.3). However, in the gap region where ideal flow assumptions are valid, there is no reason for reducing the magnitude of V_N by a fraction determined by the value of the discharge coefficient. Besides, it is worth mentioning that the

Fig. 7.2.2.2 Implication Of the Discharge Coefficient When Applied to the Mass Flow Rate Through the Tip Gap

Fig. 7.2.2.3 Implication Of the Discharge Coefficient When Used In the Calculation of the Velocity Component Normal to the Blade Meanline

global reduction in V_N will also effect the resultant flow angle through the gap. Furthermore, when the discharge coefficient is included into the calculation of V_N , as is seen from equation 7.2.2.1, a discharge coefficient less than 1 implies a total pressure loss. This is certainly not the purpose of this discharge coefficient whose definition is based on mass flow rate considerations. Thus it is unlikely that the experimentally derived values of this discharge coefficient also give the correct total pressure loss.

In the light of these arguments, both Booth's Model and the Simple Model were modified so that the discharge coefficient is used in the conventional way (i.e., it is used to determine the actual mass flow rate once the ideal mass flow rate is calculated; $m_{\text{actual}} = C_D m_{\text{ideal}}$). The models that take into account the modification discussed in this paragraph will be referred to as the "Modified Booth's Model" and "Modified Simple Model". A summary of the examined models and the aspects in which they differ from each other are given in Table 7.2.2.1. The source code of the programs for Booth's Model and the Modified Simple Model is given in Appendix H.

It should be noted that since the Modified Simple Model includes all the necessary modifications discussed so far in this section, it is expected to be the most successful one among the other models noted above.

Model	Pressure Difference for Calculating V_N	Discharge Coefficient Location
Booth's Model	Along the tip gap streamline	Energy equation
Simple Model	Normal to the blade chord	Energy equation
Modified Booth's Model	Along the tip gap streamline	Continuity equation
Modified Simple Model	Normal to the blade chord	Continuity equation

Table 7.2.2.1 Examined Tip Leakage Models

One more point to be considered is that in order to use Booth's Model and the Simple Model, the discharge coefficient has to be known at the beginning of the calculations since it is used in determining the normal velocity (see equation 7.2.1.1). Booth et al. (1982) used a discharge coefficient of 0.3 which they obtained from their experiments (see section 2.12). Since one of the intentions herein is to check the validity of this quoted value for the discharge coefficient, the programs for Booth's Model and the Simple Model repeat the calculations for various discharge coefficients until the calculated mass flow rate matches the actual one. Of course this type of an iteration is not necessary in the modified versions of Booth's Model and the Simple Model.

7.2.3 Discussion of the Discharge Coefficient Values

The discharge coefficients obtained from Booth's Model, the Simple Model and their modified versions are given in Table 7.2.3.1. Since the trend of the results is similar for all four models, only the result for the Modified Simple Model, which includes all the suggested modifications to Booth's Model, will be discussed. From the results for $t/c = 0.02845$ and 0.01931 it is observed that the value of the discharge coefficient increases with decreasing clearance height. As was discussed earlier, the conventional purpose of the discharge coefficient is to correct

	$\left(\frac{t}{c} = 0.03175 \right)$	$\left(\frac{t}{c} = 0.02845 \right)$	$\left(\frac{t}{c} = 0.01981 \right)$
	C_D	C_D	C_D
Booth's Model	0.655	0.611	0.755
Simple Model	0.640	0.603	0.746
Modified Booth's Model	0.679	0.632	0.772
Modified Simple Model	0.659	0.623	0.765

Table 7.2.3.1 Discharge Coefficients For The Tip Clearance Mass Flow Rate, Calculated Using Various Leakage Models ($Re = 4.3E05$)

the mass flow rate due to regions where the flow behaviour does not agree with the ideal flow assumptions. In this case the assumptions obviously break down in the separation bubble on the blade tip. As was concluded from the three-hole probe measurements, the size of this bubble relative to the tip clearance height reduces with decreasing clearance height. This means that with decreasing gap height an increase in the discharge coefficient should be expected, which is in fact the observed result.

As seen from Fig. 7.2.3.1, the discharge coefficient is slightly higher for $t/c = 0.03175$ than for $t/c = 0.02845$. As noted earlier, these two cases differ not only in the height of the gap but also in the thickness of the incoming boundary layer and the levels of free stream turbulence. The results thus suggest that those factors may have some influence on the discharge coefficient. However, it appears that the primary factor is the height of the tip gap relative to the dimensions of the blade.

As was noted in the previous section, in their model Booth et al. used an experimentally derived discharge coefficient value of 0.8. They noted that this value remained the same regardless of the clearance size. Apparently, this quoted value was also obtained by Moore & Tilton (1987) from their experiments with a single gap size. However, as was discussed in the previous

Fig. 7.2.3.1 Discharge coefficient Variation With Clearance Size

paragraphs, the present results clearly show a reduction in the discharge coefficient value as the clearance size is increased.

7.2.4 Comparison of the Experimental Results With the Ones Obtained Using the Leakage Models

As was mentioned earlier, knowing the actual mass flow rate for each clearance height examined, the correct discharge coefficient values were determined for use in the calculations for the leakage models. This implies that at this stage the leakage model calculation procedures can not really be considered as predictions. Nevertheless, once the variation of the discharge coefficient with clearance height is determined from the correlation presented in the previous section, in future studies these models can be used for prediction. Therefore, even though for now this is not exactly the case, the quantities obtained from the models will be referred to as the predicted values.

For $t/c = 0.03175$, the tip clearance mass flow rate, flow angle and resultant velocity distribution obtained from Booth's Model and the Simple Model are compared to the experimental results in Figures 7.2.4.1, 7.2.4.2 and 7.2.4.3 respectively. Since the models are supposed to predict well the tip clearance flow out of the separation bubble region, the experimental velocities and flow angles used for the comparison were obtained by averaging the measurements taken outside the bubble. As can be seen, both

Fig. 7.2.4.1 Tip Clearance Mass Flow Rate Distribution
($Re = 4.3E05$)

Fig. 7.2.4.2 Tip Clearance Flow Angle Distribution
 $t/c = 0.03175$ $Re = 4.3E05$

Fig. 7.2.4.3 Tip Clearance Resultant Velocity Distribution

$t/c = 0.03175$ $Re = 4.3E05$

models give essentially the same distributions for all three quantities except very close to the leading edge where the simple model is marginally better in the mass flow rate prediction. However, due to its agreement with physical insight and due to its relatively simple calculation procedure, the Simple Model should be preferred. As far as agreement with experimental distributions is concerned, from the plots one can see that the flow angle and the mass flow rate distribution is predicted reasonably well except very close to the leading edge where the experimental results indicate a sudden drop in the mass flow rate and a rapid change in the flow angle. Note that on the mass flow rate plot, after the peak location the agreement between the actual and theoretical curves is also not very good. This might be due to the calibration change of the three-hole-probe since, as was discussed in section 7.1, this is the part of the gap where the effect of the probe calibration change on the tip clearance mass flow rate was seen.

If the resultant velocity distributions are compared (Fig. 7.2.4.3), the predicted velocities appear to be considerably lower than the experimental ones. This disagreement is explained by the reasoning given in the previous section which resulted in the introduction of the modified versions of Booth's Model and the Simple Model: if the discharge coefficient is not used in the normal velocity calculation, the resultant velocity would be of higher magnitude which would mean a better agreement in Fig.

7.2.4.3. Besides, with the increased normal velocity the predicted flow direction would be closer to the direction normal to the chord which would improve the agreement in Fig. 7.2.4.2. These improvements can clearly be seen in Figures 7.2.4.4 to 7.2.4.6, where the results of the Modified Original Model and Modified Simple Model are compared to experimental results.

So far, only the results for the largest tip clearance are presented. The observations for the other two clearances are very similar to the ones for $t/c = 0.03175$ and for reference the plots for those cases are given in Appendix I.

As can be seen from the results, while all four models predict the mass flow rate distribution with essentially the same accuracy, only the modified versions predict it for the right physical reasoning. Furthermore, the leakage model improvements suggested in section 7.2.2 lead to considerable increase in the accuracy of the predicted tip gap velocity and flow angle distribution. Therefore, the Modified Simple Model, which takes into account all the suggested modifications, is the one suggested at the end of this work and can be used as a basis for further studies. Furthermore, unlike the results in the available literature, the value of the discharge coefficient was found to be dependent on the clearance size and the results given in Fig. 7.2.3.1 can be used with the Modified Simple Model or any other prediction method that may be available in the future.

Fig. 7.2.4.4 Tip Clearance Mass Flow Rate Distribution
($Re = 4.3E05$)

Fig. 7.2.4.5 Tip Clearance Flow Angle Distribution
 $t/c = 0.03175$ $Re = 4.3E05$

Fig. 7.2.4.6 Tip Clearance Resultant Velocity Distribution

$t/c = 0.03175$ $Re = 4.3E05$

8. Reynolds Number Effects

Another aspect that might be important for the tip clearance flow is the effect of Reynolds number. In order to determine whether the tip clearance flow is altered with changes in the Reynolds number, the blade and endwall static pressure measurements were repeated for a range of Reynolds numbers. The three-hole probe measurements within the clearance were also repeated for a Reynolds number approximately half of the original value. While varying the Reynolds number, the inlet endwall boundary layer characteristics can change. Therefore, in order to ensure that these changes are not very significant, for a number of representative Reynolds numbers selected from the Reynolds number range considered, the boundary layer was traversed $2/3c$ upstream of the blade row. The boundary layer velocity distributions are shown in Fig. 3.1 and the layer parameters are given in Table 8.1. As can be seen, with increasing Reynolds number the displacement and momentum thicknesses are slightly decreased, which is expected.

Blade static pressures for the largest clearance ($t/c = 0.03175$) were measured at row 1 and at midspan for four different Reynolds numbers and are presented in Figures 8.2 and 8.3 respectively. From these figures it is observed that with increasing Reynolds number the pressure and suction side pressure distribution curves at both midspan and row 1 shift slightly to

Fig. 8.1 TEST SECTION INLET END WALL BOUNDARY LAYER VELOCITY PROFILES

	δ^*/h	θ/h	H
Re = $4.3 \cdot 10^5$	0.00731	0.00544	1.344
Re = $2.4 \cdot 10^5$	0.00988	0.00719	1.375
Re = $1.6 \cdot 10^5$	0.01285	0.00909	1.414

Table 8.1 Inlet Endwall Boundary Layer Parameters
For Three Reynolds Numbers
($t/c = 0.03175$)

Fig. 8.2 BLADE SURFACE C_p DISTRIBUTION
($t/c = 0.03175$ ROW 1)

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Fig. 8.3 BLADE C_p DISTRIBUTION
($t/c = 0.03175$ ROW 14)

lower pressures towards the trailing edge. Since the shift occurs about equally for both suction and pressure side curves, this will not affect the blade pressure difference very much. In order to observe how the endwall driving pressure difference is affected, the endwall static pressures were measured for three different Reynolds numbers and the driving pressure difference was calculated as explained in section 5.2. These results together with the midspan blade pressure differences are presented in Fig. 8.4. As can be seen, there is not a distinct variation with changes in Reynolds number. The endwall pressures are also presented as contour plots in Figures 8.5 and 8.6 and they again show very similar distributions for different Reynolds numbers.

However, with variations in the Reynolds number there is a change in the shape of the suction peak in row 1. This indicates that the structure of the tip leakage vortex has slightly altered close to the region where the vortex starts to form. The change can clearly be seen by comparing the results of row 1 presented in Fig. 8.2. With increasing Reynolds number the tip of the suction peak becomes wider. In the previous discussions it was observed that the separation bubble on the blade tip and the tip leakage vortex were interactive structures. Therefore, the slight change in the tip leakage vortex structure may be due to a change in the separation bubble size. The change does not appear to be due to changes in the inlet endwall boundary layer.

Fig. 8.4 DRIVING PRESSURE DIFFERENCE DISTRIBUTION ($t/c = 0.03175$)

Fig. 8.5 Endwall C_p Distribution ($t/c = 0.01981$,
 $Re = 4.3 \cdot 10^5$)

Fig. 8.6 Endwall C_p Distribution ($t/c = 0.01981$,
 $Re = 1.5 \cdot 10^5$)

For example, at row 1 the blade pressures for $t/c = 0.03175$ and 0.02845 at $Re = 4.3 \times 10^5$ (see section 5.1), are very similar even though the differences in the boundary layer parameters are substantially larger than the differences caused by Reynolds number changes at a given clearance size. That the variations with Reynolds number are associated with the separation bubble is supported by the flow field measurements within the gap. The velocity vector distribution for $Re = 2.4 \times 10^5$, $t/c = 0.03175$ is given in Fig. 8.7. Comparing this result to the one obtained for $Re = 4.3 \times 10^5$, $t/c = 0.03175$ (Fig. 8.8), it is seen that in the region corresponding to the suction peak, the separation bubble increases in size when the Reynolds number is decreased. This is also supported by the total pressure loss contours given in Figures 8.9 and 8.10. Therefore, it can be concluded that the change in the suction peak shape is a result of the local variation of the separation bubble size with Reynolds number.

It is worth mentioning that Shalnev (1958) (as quoted by Gearhart (1966)), from his experiments on gap cavitation (which is caused by the low pressures in the separation bubble on the blade tip), states that the relative bubble size does not change with Reynolds number. The present results thus imply that this is not a general result for the whole blade length.

From the comparison of Figures 8.7 and 8.8, it is observed that other than the slight change in the separation bubble structure,

BLADE TIP

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SEE OVER

Fig. 8.7 Velocity and Flow Angle Distribution
Along the Blade Meanline ($t/c = 0.03175$,
 $Re = 2.4 \cdot 10^6$)

1/16 IN

4.4 2/1 (%)

1/16 IN

30

1/16 IN

10.8

1/16 IN

36.4

1/16 IN

17.2

1/16 IN

42.8

1/16 IN

23.6

1/16 IN

49.2

SEE OVER

Fig. 8.8 Velocity and Flow Angle Distribution
Along the Blade Meanline ($t/c = 0.03175$,
 $Re = 4.3 \cdot 10^6$)

Fig. 8.9 Tip Clearance Total Pressure Loss Coefficient Distribution ($t/c = 0.03175$, $Re = 4.3 \times 10^5$)

Fig. 8.10 Tip Clearance Total Pressure Loss Coefficient Distribution ($t/c = 0.03175$, $Re = 2.4 \cdot 10^5$)

the velocity magnitude and the flow angle distribution along blade meanline are essentially the same for Reynolds numbers 4.3×10^5 and 2.4×10^5 . This is consistent with the driving pressure difference through the gap being unchanged as indicated by the endwall static pressure measurements.

The mass flow rate calculated from the three-hole probe measurements for $Re = 2.4 \times 10^5$ was found to be slightly lower than for the higher Reynolds number. The difference between those mass flow rates is only about 1.6%. From the chordwise distribution of the mass flow rate shown in Figure 8.11, it is seen that the distributions are essentially the same except in the region of 30% to 45% of the chord length. As was discussed in the previous paragraph, the separation bubble size increases within this region and thus would be expected to result in the observed, with decreasing Reynolds number. This portion of the clearance is also out of the region where one would expect the change in the probe calibration to significantly affect the chordwise mass flow rate distribution (see section 7.1).

Therefore, it is reasonable to conclude that the observed change in the tip clearance mass flow rate is real. Considering these observations, one would expect the discharge coefficient for the low Reynolds number case to be slightly smaller than the one for the higher Reynolds number which, as shown in Table 8.2, is in fact the case.

Fig. 8.11, Tip Clearance Mass Flow Rate Distribution

	Re = 2.4E05	Re = 4.3E05
	C_p	C_p
Booth's Model	0.655	0.635
Simple Model	0.640	0.620
Modified Booth's Model	0.679	0.658
Modified Simple Model	0.659	0.640

Table 8.2 / Discharge Coefficients at Two Different
Reynolds Numbers ($t/c = 0.03175$)

9. Conclusions and Recommendations for Future Studies

9.1 Conclusions

As was noted in Chapter 2, the blade surface pressure distribution close to the blade tip has been widely used as a basis for understanding the effects of the tip clearance flow. These measurements were also taken in the present study. These recent results essentially support the observations from earlier studies, such as the formation of the main tip leakage vortex at about 25% chord length from the leading edge, the increase of its diameter when proceeding towards the exit of the blade passage, the effect of this vortex on the blade suction surface pressure distribution. To some extent, the presence of smaller tip leakage vortices, which form further downstream of the main tip leakage vortex, was also observed. Besides these results, which have already been seen in previous studies, the blade surface pressure measurements along with other measurements described below, enabled the clarification of many other features associated with the tip clearance flow.

As was stated by Rains (1954), for clearance sizes seen in practice the pressure difference across the tip clearance is the dominant factor which drives the clearance flow. Therefore, being able to predict its magnitude along the blade length is an important issue. Since the blade pressure difference close to

the blade tip varies significantly in the spanwise direction, prediction methods which attempt to relate pressure differences measured near the tip to the tip gap flow are very questionable. The detailed endwall static pressure measurements showed that, for clearance sizes used in practice, the pressure difference that drives the tip clearance flow close to the endwall is in fact essentially the undisturbed (i.e., two-dimensional) blade pressure difference. The velocity distribution obtained from the detailed three-hole probe measurements within the tip gap indicated that this is also valid for gap regions further away from the endwall. Thus, for practical clearance sizes the driving pressure difference for the tip gap flow can simply be calculated using the two-dimensional blade surface pressure distribution, which is easily determined either experimentally or analytically.

The endwall static pressures showed that the pressure maxima and minima do not fall on the contour which follows the blade shape. The pressure minimum appears to be inside the gap while the pressure maximum is located somewhat further away (into the passage) from the tip gap entrance. This indicates that the flow completes its acceleration normal to the blade chord before it enters the gap. Therefore, relating the tip gap flow to the endwall static pressures located on a contour following the blade shape, as is done by a few authors, will give very misleading results.

The three-hole probe measurements within the tip gap enabled a very detailed examination of the tip clearance flow. From these measurements the separation bubble caused by the sharp turning at the pressure surface corner was clearly observed. The bubble size appeared to reach its peak value at the location where the main tip leakage vortex starts to form, showing the close interaction between the bubble and the vortex. After reaching its peak size at about 25% c, for the rest of the blade length the bubble continued to cover a major portion of the blade thickness. Interestingly, the flow within the separation bubble resembled more a vortical flow, distinguishing this structure from a regular two-dimensional separation bubble. As far as the amount of tip leakage is concerned, the separation bubble is in a way a useful structure since it reduces the amount of fluid that passes through the tip gap. In this connection it was observed that the separation bubble size was about 30 to 40% of the clearance height and its size relative to the gap height appeared to drop with decreasing clearance size. Finally, a reduction in Reynolds number appeared to increase the bubble size at the location where it reaches its peak size. This was clearly reflected in the shape of the blade surface suction peak which appears where the tip leakage vortex starts to form. This is another indication of the close interaction between the separation bubble and the leakage vortex, mentioned in the previous paragraph.

Out of the separation bubble the observed total pressure losses were very small or zero, indicating that the tip leakage flow essentially consists of free stream fluid. Note that this is an important observation as far as modeling the tip leakage flow is concerned. The velocity and flow angle distributions within the tip gap showed that out of the separation bubble the velocity magnitude and directions are very similar for all three clearances examined. This is consistent with the observations concerning the tip leakage driving pressure difference, discussed above. The results also indicated that the velocity component normal to the blade chord is of about the same magnitude at gap entrance and exit. This clearly shows that the flow accelerates before entering the tip gap, confirming the conclusion drawn from the endwall static pressure measurements. The calculated tip clearance mass flow rate based on these measurements showed that when the clearance size is reduced, the percentage reduction in the mass flow rate is less than the percentage reduction in the clearance height. This is consistent with the variation of the relative size of the separation bubble discussed above.

Due to the lack of detailed and accurate measurements in the tip gap, very few studies have been done on modeling the flow within the tip clearance. For the same reason, the assumptions built into the available models could not be verified. The present experimental results were used to check the success of

the leakage model of Booth et al., which is apparently the most extensive model available in the literature. The assumptions that the tangential momentum is conserved across the gap, that the stream line across the gap is straight and that the fluid entering the gap is essentially free stream fluid were confirmed. On the other hand, some improvements were suggested which not only increased the accuracy of the model, but also greatly simplified the calculation scheme:

- It was found that the velocity component normal to the blade chord should be calculated from the pressure difference normal to the chord rather than the pressure difference along the tip leakage streamline which is the case in Booth's model. This modification improves the agreement of the tip clearance chordwise mass flow rate distribution with experimental results only marginally. On the other hand it is a necessary modification so as to model the real flow properly and it also considerably simplifies the calculation scheme.

- Booth et al. used the discharge coefficient within the Bernoulli equation to calculate the tip leakage velocity component normal to the blade chord. It was found that if the discharge coefficient is used in the conventional way (i.e., to adjust the resultant ideal mass flow rate so as to match the actual one) instead, the agreement of the predicted tip leakage velocity magnitude and flow angle with experimental results is

significantly improved.

In this connection it should be noted that, unlike the observations in previous studies, the discharge coefficient appeared to be dependent on the clearance size. This is explained by the variation of the relative separation bubble size with clearance height.

9.2 Recommendations

The work presented herein gave a detailed picture of the flow within the tip gap. On the other hand, even though the blade surface and endwall static pressure measurements showed to some extent how the passage flow is affected by the tip leakage flow, these results are not complete until they are analyzed in conjunction with measurements at the blade row exit. These downstream measurements will also give the circulation associated with the tip leakage vortex. This is significant since it is used in a number of models for predicting various properties, such as over and under-turning and the loss distribution in the downstream flow.

The present study enabled the determination of the losses that occur within the tip clearance. This result should be compared to the additional losses which occur as the tip leakage vortex mixes out downstream of the blade row. This comparison will

identify the mechanism which accounts for the dominant portion of the losses, and thus will yield to the most effective design modifications.

The present results suggest that the endwall boundary layer parameters have only a secondary effect on the tip clearance flow. However, this conclusion is only tentative since the inlet boundary layer was not varied intentionally, and some other parameters were also changed at the same time. Therefore, a future study investigating purely the endwall boundary layer effect on tip clearance flow would be useful.

The tip clearance measurements performed in this study gave the chordwise distribution of the tip clearance mass flow rate. This can certainly be used as a basis of future studies aimed towards the determination of the optimum blade tip and casing treatments, so as to effectively reduce the mass flow rate through the tip gap.

The detailed measurements within the tip gap enabled the analysis of the degree of success of the extensive leakage models available in the literature. Also, in the light of the observations, a number of significant improvements to these models was suggested. On the other hand, particularly in the tip gap region close to the leading edge the predictions are still not very good and require further investigation.

Finally, the effect of endwall motion on the discharge coefficient is another aspect that certainly needs to be studied.

REFERENCES

AINLEY, D. G.	1951	"A Method of Performance Estimation for Axial-Flow Turbines", British ARC R&M 2974, 1951.
MATHIESON, G. C. R.		
ALLEN, H. W.	1955	"Visualization Study of Secondary Flows in Turbine Rotor Tip Regions", NACA TN 3519, 1955.
KOFSKEY, M.G.		
AMANN, C. A.	1963	"Consideration in the Design Development of Turbines for Automotive Gas Turbine Engines", SAE Paper 653, January 1963.
DAWSON, D. W.		
YU MASON, K.		
AMRUD, K. K.	1985	"Tip Leakage In A Planar Cascade of Turbine Blades", Carleton U., M.Eng. Thesis, 1985.
BECKER, H. A.	1974	"Response of Pitot Probes in Turbulent Streams", Journal of Fluid Mechanics, Vol. 62 Ptl, 1974, pp. 85-114.
BROWN, A. P. G.		
BETTNER, J. L.	1983	"The Influence of Tip Clearance Stage Loading, and Wall Roughness on Compressor Casing Boundary Layer Development, Vol. 105, April 1983, pp. 280-287.
ELROD, C.		

- BETZ, A. 1926 "Hydraulische Probleme", VDI Verlag-Berlin, 1926.
- BINDON, J. P. 1986 "Pressure and Flow Field Measurements of Axial Turbine Tip Clearance Flow in a Linear Cascade", Report No. CUED/A-Turbo TR123, Whittle Laboratory, Cambridge University, 1986.
- BINDON, J. P. 1987 "Visualization of Tip Clearance Flow in a Linear Turbine Cascade", To be presented at the 8th International Symposium on Air Breathing Engines, Cincinnati, 1987.
- BOOTH, T. C. 1985 "Tip Clearance Effects in Axial Turbomachines", Von Karman Institute for Fluid Dynamics, Lecture Series 1985-05, April 1985.
- BOOTH, T. C. 1982 "Rotor-Tip Leakage: Part I-Basic Methodology", Journal of Engineering for Power, Vol. 104, January 1982, pp. 154-161.
- DODGE, P. R.
- HEPWORTH, H. K.
- BOYCE, M. P. 1975 "Study of Casing Treatment Effects in Axial Flow Compressors", Journal of Engineering for Power,
- SCHILLER, R. N.
- DESAI, A. R.

October 1975, pp. 477-483.

- CRAIG, H. R. M. 1970 "Performance Estimation of Axial Flow
COX, H. J. A. -71 Turbines", Proc. Instn. Mech. Engrs.,
Vol. 185, No. 32, 1971, pp. 407-424.
- DEAN, R. C. 1954 "The Influence of Tip Clearance on
Boundary-Layer Flow in a Rectilinear
Cascade", M.I.T. Gas Turbine
Laboratory, No. 27-3, 1954.
- DUNHAM, J. 1970 "Improvements to the Ainley &
CAME, P. M. Mathieson Method of Turbine
Performance Prediction", ASME Journal
of Engineering Power, July 1970,
pp. 252-256.
- FUJIE, K. 1962 "A Study of the Flow Through the Rotor
of an Axial-Compressor - A
Proposition of Formulas of Drag
Coefficients", Bull. Japan.
Soc. Mech. Engrs., Vol. 5, No. 18,
1962.
- FUTRAL, S. M. 1968 "Experimental Performance of a 5-inch
HOLESKI, D. E. (13 cm) Axial-Flow Turbine Over a
Range of Reynolds Number", NASA TM
X-1679, June 1968.

- GABRAITH, R. A. McD. 1975 "Eddy Viscosity and Mixing Length
HEAD, M. R. from Measured Boundary Layer
Developments", Aero. Quarterly,
Vol. 26, May 1975, pp. 133-154.
- GEARHART, W. S. 1966 "Tip Clearance Cavitation in Shrouded
Underwater Propulsors", Journal of
Aircraft, Vol. 3, No. 2, March -
April 1966, pp 185-192.
- GOLDSTEIN, S. 1936 "A Note on the Measurement of total
Head and Static Pressure in a
Turbulent Stream", Proc. Royal
Soc., Series A, Vol. 155, 1936,
pp. 570.
- GLASSMAN, A. J. 1973 "Turbine Design and Application",
Vol. II, NASA SP-290, 1973.
- GRAHAM, J. A. H. 1986 "Investigation of a Tip Clearance
Cascade in a Water Analogy Rig",
Journal of Engineering for Gas
Turbines and Power, Vol. 108,
January 1986, pp. 38-46.
- GRANT, R. J. 1983 "Effect of Casing Separations and Tip
Leakage Jets on Turbine Efficiency",
JOHNSON, C. G. Int. J. Heat & Fluid Flow, Vol. 4,
WILKINSON, D. H. No. 4, December 1983, pp. 239-245.

- HAAS, J. E. 1977 "Cold-Air Performance of a 12.766-Centimeter-Tip-Diameter Axial-Flow Cooled Turbine", NASA TP 1032, June 1977.
- KOFSKEY, M. G.
- HESSELGREAVES, J. E. 1969 "A Correlation of Tip-Clearance/Efficiency Measurements on Mixed-Flow and Axial-Flow Turbomachines", National Engineering Laboratory (England) Report No. 423, September 1969.
- HONG, YONG S. 1966 "Axial Turbine Loss Analysis and Efficiency Prediction Method", Rep. D4-3220, Boeing Co., March 1966.
- GROH, F. G.
- HUBERT, G. 1960 "Investigations of Three Dimensional Flow Through Compressor Cascades and Stator", Zeitschrift Flugwiss, Vol. 8, 1960, p. 226.
- HUNTER, I. H. 1982 "Endwall Boundary Layer Flows and Losses in an Axial Turbine Stage", Journal of Engineering for Power, Vol. 104, January 1982, pp. 184-193.
- HUPPERT, C. M. 1953 "Some Stall and Surge Phenomena in Axial Flow Compressors", Lewis Flight Propulsion Laboratory, NACA,
- BENSER, W. A.

Presented at the Flight Propulsion
Session, 21st. Annual Meeting, IAS
New York, January 26-29, 1953.

- HUTTON, S. P. 1956 "Three-Dimensional Motion in Axial
-Flow Impellers", Proc. I. Mech. E.,
Vol. 170, No. 25, 1956, pp. 863-873.
- INOUE, M. 1984 "Three-Dimensional Structure and Decay
KUROUMARU, M. of Vortices Behind an Axial Flow
Rotating Blade Row", Journal of
Eng. for Gas Turbines and Power,
Vol. 561, July 1984, pp. 561-569.
- INOUE, M. 1986 "Behaviour of Tip Leakage Flow Behind
KUROUMARU, M. an Axial Compressor Rotor", Journal
of Engineering for Gas Turbines and
FUKUHARA, M. Power, Vol. 108, January 1986,
pp. 7-14.
- ISHIDA, M. 1981 "On the Pressure Losses Due to the
SENOO, Y. Tip Clearance of Centrifugal
Blowers", Journal of Engineering for
Power, Vol. 103, April 1981, pp. 271
-278.
- JEFFERSON, J. L. 1958 "Some Shrouding and Tip Clearance
TURNER, R. C. Effects in Axial Flow Compressors",
International Ship Builder Progress,

Vol. 5, No. 42, February 1958,
pp. 78-101.

- KACKER, S. C. 1982 "A Mean Line Prediction Method for
OKAPUU, U. Axial Flow Turbine Efficiency", ASME
Journal of Engineering for Power,
Vol. 104, January 1982, pp. 111-119.
- KHABBAZ, G. R. 1959 "The Influence of Tip Clearance on
Stall Limits of a Rectilinear Cascade
of Compressor Blades", Gas Turbine
Laboratory Report No. 54, M.I.T.,
August 1959.
- KHABBAZ, G. R. 1961 "The Influence of Tip Clearance on
SENNOO, Y. Stall Limits of a Rectilinear Cascade
of Compressor Blades", Journal of
Basic Engineering, September 1961,
pp. 371-378.
- KLEIN, A. 1966 "Untersuchungen Über den Einfluss der
Zustromgrenzschicht auf die
Sekundärströmungen in den
Beschaufelungen von Axialturbinen",
Forsch. Ing. Wes. 32, Nr. 6, 1966,
p. 175.
- KOFSKEY, M. G. 1961 "Experimental Investigation of Three
Tip-Clearance Configurations over a

Range of Tip Clearance Using a
Single-Stage Turbine of High Hub to
Tip Radius ratio", NASA TM No. X-472,
January 1961.

- KOFSKEY, M. G. 1967 "Performance Evaluation of a Two Stage
NUSBAUM, W. J. Axial-Flow Turbine for Two Values of
Tip Clearance", NASA TN. D. 4388,
October 1967.
- LAKSHMINARAYANA, B. 1970 "Methods of Predicting the Tip
Clearance Effects in Axial Flow
Turbomachinery", Journal of Basic
Engineering, Vol. 104, 1970,
pp. 467-482.
- LAKSHMINARAYANA, B. 1985 "Tip Clearance Effects in Axial
Turbomachines", Von Karman Institute
for Fluid Dynamics, Lecture Series
1985-05, April 1985.
- LAKSHMINARAYANA, B. 1982 "Characteristics of Mean Velocity in
DAVINO, R. M. the Tip Region of Turbomachinery
Rotor Exit", AIAA, Vol. 20, No. 4,
April 1982, pp. 528-535.
- LAKSHMINARAYANA, B. 1982 "Three-Dimensional Flow Field in the
DAVINO, R. M. Tip Region of a Compressor Rotor
POUAGARE, M. Rotor Passage-Part II: Turbulence

Properties", Journal of Engineering for Power, Vol. 104, October 1982, pp. 772-781.

- LAKSHMINARAYANA, B. 1962 "Tip-Clearance Flow and Losses for an
HORLOCK, J. H. Isolated Compressor Blade", ARC R&M
3316, 1962.
- LAKSHMINARAYANA, B. 1965 "Leakage and Secondary Flows in
HORLOCK, J. H. Compressor Cascades", ARC R&M 3483,
1965.
- LANGSTON, L. S. 1977 "Three-Dimensional Flow Within a
NICE, M. L. Turbine Cascade Passage", Journal of
HOOPER, R. M. Engineering for Power, January 1977,
pp. 21-28.
- LEWIS, R. I. 1977 "Vortex Shedding Mechanisms In
YEUNG, E. H. C. Relation to Tip Clearance Flows and
Losses in Axial Fans", ARC R&M 3829,
May 1977.
- LEWIS, W. E. 1966 "Fixed-Direction Probes for
Aerodynamic Measurements", Proc.
Inst. Mech. Engrs., Vol. 180, Pt.3J,
1965-66, pp. 141-152.
- MACMILLAN, F. A. 1954 "Viscous Effects on Pitot Tubes at
Low Speeds", J. Royal Aero. Soc.,

August 1954, pp. 570-572.

- MACMILLAN, F. A. . 1954 "Viscous Effects on Flattened Pitot Tubes at Low Speeds", J. Royal Aero. Soc., December 1954, pp. 837-839.
- MACMILLAN, F. A. 1956 "Experiments on Pitot Tubes in Shear Flow", ARC R&M 3028, 1956.
- McNAIR, R. E. 1960 "Tip Clearance Effects on Stalling Pressure Rise in Axial Flow Compressors", [Abridged contents of papers], Symposium on Compressor Stall, Surge and System Response, Houston, Texas, March 6-9, 1960, pp. 47-50.
- MEHMEL, D. 1962 "Clearance Flow in Cascades", Ingenieur-Archiv, Vol 31, 1962, pp. 294-300.
- MELDAHL, A. 1941 Brown Boveri Review, Vol. 28, 1941, p. 356.
- MOORE, J. 1987 "Tip Leakage Flow in a Linear Turbine Cascade", ASME 87-GT-222, 1987.
- TILTON, J. S.
- MOORE, R. D. 1977 "Effects of Tip Clearance on Overall Performance of Transonic Fan Stage With and Without Casing Treatment",
- OSBORN, W. M.

NASA TM X-3479, February 1977.

- MOUSTAPHA, H. 1986 "Turbomachinery Course Handbook",
Carleton U., Faculty of Engineering,
Department of Mech. & Aero.
Engineering, 1986.
- OZARAPOGLU, V. 1973 "Measurements in Incompressible
Turbulent Flow", PhD Thesis, Laval,
June 1973.
- PANDYA, A. 1983 "Investigation of the Tip Clearance
Flow Inside and at the Exit of a
Compressor Rotor Passage- Part I:
Mean Velocity Field", Journal of
Engineering for Power, Vol. 105,
January 1983, pp. 1-12.
- LAKSHMINARAYANA, B.
- PANDYA, A. 1983 "Investigation of the Tip Clearance
Flow Inside and at the Exit of a
Compressor Rotor Passage- Part II:
Turbulence Properties", Journal of
Engineering for Power, Vol. 105,
January 1983, pp. 13-17.
- LAKSHMINARAYANA, B.
- PATEL, K. V. 1980 "Research on a High Work Axial Gas
Generator Turbine", Society of
Automotive Engineers, Inc., 1980.

- PEACOCK, R. E. 1982 "A Review of Turbomachinery Tip Gap Effects - Part 1 : Cascades", Int. J. Heat & Fluid Flow, Vol. 3, NO. 4, December 1982, pp. 185-193.
- PEACOCK, R. E. 1983 "A Review of Turbomachinery Tip Gap Effects - Part 2 : Rotating Turbomachinery", Int. J. Heat & Fluid Flow, Vol. 4, No. 1, March 1983, pp. 3-16.
- PHILLIPS, W. R. C. 1980 "Flow Visualization in the Tip Region of a Rotating Blade Row", J. Mech. Science, Vol. 22, January 1980, pp. 495-521.
- HEAD, M. R.
- RAINS, D. A. 1954 "Tip Clearance Flows in Axial Flow Compressors and Pumps", California Institute of Technology, Hydrodynamics and Mechanical Engineering Laboratories, Report No. 5, June 1954.
- REEDER, J. A. 1968 "Tip Clearance Problems in Axial Compressors (A Survey of Available Literature)", A.E.C. Research and Development Report No. K-1682, Union Carbide Corporation, Nuclear

Division, 1968.

- REHBACH, J. 1960 "Untersuchung der Spaltverluste von Turbinenleitradern mit Bewegter Spaltwand", Forsch. Ing. Wes., Bd.26, 1960, pp. 58-61.
- ROGO, C. 1968 "Experimental Aspect Ratio and Tip Clearance Investigation on Small Turbines", SAE paper 680448, Mid year meeting Detroit, Mich., May 20-24, 1968.
- SENOO, Y. 1986 "Pressure Loss Due to the Tip Clearance of Impeller Blades in Centrifugal and Axial Blowers", Journal of Engineering for Gas Turbines and Power, Vol. 108, January 1986, pp. 32-37.
- ISHIDA, M.
- SIEVERDING, C. H. 1985 "Recent Progress in the Understanding of Basic Aspects of Secondary Flows in Turbine Blade Passages", Journal of Engineering for Gas Turbines and Power, Vol. 107, April 1985, pp. 248-257.
- SIEVERDING, C. H. 1983 "The Use of Coloured Smoke to Visualize Secondary Flows in a
- VAN DEN BOSCHE, P.

Turbine-Blade Cascade", J. Fluid Mech., Vol. 134, 1983, pp 85-89.

- SJOLANDER, S. A. 1975 "The Endwall Boundary Layer In An Annular Cascade of Turbine Nozzle Guide Vanes", Carleton U., TR ME/A 75-4, 1975.
- SJOLANDER, S. A. 1986 "Effects of Tip Clearance on Blade Loading in a Planar Cascade of Turbine Blades", ASME Gas Turbine Conference Paper, Paper No. ASME 86-GT-245, 1986.
- AMRUD, K.
- SUGIYAMA, Y. 1970 "On the Characteristics of Wing With Tip Clearance (Part 2)", Bulletin of JSME, Vol. 13, No. 58, 1970, pp. 542-553.
- SUGIYAMA, Y. 1975 "On the Characteristics of a Wing With a Tip Clearance (Part 5)", Bulletin of JSME, Vol. 18, No. 123, September 1975, pp. 984-991.
- SUGIYAMA, Y. 1977 "Aerodynamic Characteristics of a Rectangular Wing With a Tip Clearance in a Channel", Journal of Applied Mechanics, December 1977, pp. 541-547.

LAMERS, R. P.

64-WA/FE-17, 1965.

YOKOYAMA, E.

1961 "Comparative Study of Tip Clearance
Effects in Compressors and Turbines",
M.I.T. Gas Turbine Laboratory, No.
63, 1961.

YOUNG, A. D.

1936 "The Behaviour of a Pitot Tube in a
Transverse Total Pressure Gradient",
ARC R&M 1770, 1936.

MAAS, J. N.

APPENDIX A

A) Geometric Specifications of the Pratt & Whitney Turbine Blade :

- Leading edge wedge angle = 53.99°
- Trailing edge wedge angle = 1.96°
- Maximum thickness = 0.0788"
- Blade stagger = 49.44°
- Incidence (design) = -7.48°

B) Geometric Specifications of the Turbine Cascade Blade Row:

- Scale (model/P&W prototype) = 1:12.29
- Nominal blade chord = 250 mm
- Blade height = 202.3 mm
- Blade spacing = 150 mm
- Blade maximum thickness/chord = 0.0984
- Metal turning = 59.2°
- Stagger = 38.34°
- Incidence = -10.89°

APPENDIX B

A) Blade surface tap row locations relative to the blade tip

Row #	(Distance from blade tip)/h
1	0.0212
2	0.0460
3	0.0707
4	0.0954
5	0.1201
6	0.1448
7	0.1695
8	0.1943
9	0.2190
10	0.2684
11	0.3178
12	0.3673
13	0.4167
14	0.4661

Fig. B.1 Co-ordinate System Used For Blade Surface Tap Locations

B) Tap locations relative to the co-ordinate system given in Figure B.1

<u>Tap #</u>	<u>X (inches)</u>	<u>Y (inches)</u>
(Suction Side)		
1	-3.2052	2.8267
2	-2.9803	3.0725
3	-2.7554	3.1290
4	-2.5317	3.1364
5	-2.2872	3.0971
6	-2.0844	3.0283
7	-1.8472	2.9140
8	-1.6112	2.7689 (*)
9	-1.4220	2.6276
10	-1.2155	2.4543 (*)
11	-1.0400	2.2884
12	-0.8677	2.1053
13	-0.6932	1.9049
14	-0.5334	1.7083 (*)
15	-0.3748	1.4982
16	-0.2175	1.2794
17	-0.0578	1.0483
18	0.1020	0.8136 (*)
19	0.2618	0.5715
20	0.4203	0.3232
21	0.5801	0.0701
22	0.7399	-0.1905
23	0.8984	-0.4560
24	1.0582	-0.7276
25	1.2179	-1.0053
26	1.3765	-1.2892
27	1.5363	-1.5768
28	1.6948	-1.8718
29	1.8533	-2.1704
30	2.0131	-2.4752
31	2.1716	-2.7825
32	2.3290	-3.0946
33	2.4875	-3.4105
34	2.6448	-3.7288
35	2.8033	-4.0496
36	2.9275	-4.3089 (*)
37	3.0541	-4.5682
(-Pressure Side)		
38	-3.0664	2.6104
39	-2.8980	2.5145

40	-2.7394	2.4187	(*)
41	-2.5809	2.3167	
42	-2.3830	2.1827	
43	-2.1999	2.0512	
44	-2.0070	1.9025	(*)
45	-1.8312	1.7599	
46	-1.6555	1.6100	(*)
47	-1.4809	1.4502	(*)
48	-1.3052	1.2818	
49	-1.1454	1.1208	(*)
50	-0.9857	0.9537	
51	-0.8271	0.7780	
52	-0.6673	0.5961	
53	-0.5063	0.4068	
54	-0.3466	0.2114	
55	-0.1880	0.0093	
56	-0.0283	-0.1966	
57	0.1315	-0.4093	
58	0.2913	-0.6268	
59	0.4510	-0.8480	
60	0.6108	-1.0741	(*)
61	0.7706	-1.3015	
62	0.9304	-1.5338	
63	1.0889	-1.7673	
64	1.2474	-2.0033	
65	1.4072	-2.2429	
66	1.5670	-2.4850	
67	1.7648	-2.7947	
68	2.0426	-3.2360	
69	2.2331	-3.5506	
70	2.4064	-3.8455	
71	2.5784	-4.1442	
72	2.7272	-4.4109	
73	2.8734	-4.6825	

(*) Not used during measurements

APPENDIX C

Three-hole Probe Data Reduction Program.

(The program has been coded in Turbo Pascal and is to
be compiled on an IBM compatible micro computer)

Program dataredution;

(THREE-HOLE PROBE DATA REDUCTION PROGRAM)

Type

datapoint = array [1..30] of real;

(for more than 30 points array size must be increased before
running the program)

coefmatrix = array [1..200] of real;

Var

tdate : string[20];

inp1, inp2, inp3, rwp1, rwp2, rwp3,
incmpdp, rwcmpdp, cmpdp, LossPtot, alpha : datapoint;

p1, p2, p3, ps, q, Velocity, entpd,
entvel, x, y, z, psin : datapoint;

tottemp, stctemp, rwatmps, atmprs,
density, psi, Beta, Re : datapoint;

k11, k12, k13, k23, kpsi2, kpsi3, Ptotcomp,
densinlet, dynvisc, calcof1, Testq, tipclr : real;

infile1, infile2, infile3, outfile1,
outfile2, outfile3, outfile4, outfile5,
outfile6, outfile7, outfile8 : text;

infil1, infil2, infil3, outfil1,
outfil2, outfil3, outfil4, outfil5,
outfil6, outfil7, outfil8 : string[25];

chneg, chpos : boolean;
ansrep : Char;
array1, arrayptot : coefmatrix;
matrix : array [1..21, 1..200] of real;
nofpoin, I, J, L : integer;
maxptot, nptot : integer;
maxdeg, n : array[1..21] of integer;

{

tottemp : total temperature measured in the settling chamber
(input in °F)

stctemp : static temperature at cascade inlet

rwatmps : atmospheric pressure (mm. Hg). Must be measured together
with each three-hole probe data set.

atmpres : atmospheric pressure in Pa.

densinlet : Density at cascade inlet; it is calculated from static inlet temperature and pressure.

density : Density at three-hole probe location.

array1 : Coefficient matrix; will be obtained from a part of array "matrix".

arrayptot : coef. matrix for total pressure calculation.

matrix : This array will include all the information about the calibration curves.

psi : Angle between the three-hole probe axis and the flow direction;

Beta : flow direction relative to the horizontal test rig axis.

Re : Reynolds number based on chord length and test rig entrance velocity.

Ptotcomp : Total pressure at compressor outlet; will be obtained from calibration curve.

LossPtot : total pressure loss coefficient at the measurement station $(P_{tot} - P_{tot}(inlet))/q(inlet)$.

nofpoin : number of measurement points entered into the data reduction program.

maxdeg,n : Degree of polynomial fitted to each of the calibration curve portions.

maxptot, nptot : Degree of polynomial used for "Ptot(test section inlet) & Q(Contraction pressure difference)" calibration curve.

x, y, z : Location of the measurement point (nomenclature for axis system is given in the "Test Cascade" section of the text.

alpha : Angle between the three-hole probe axis and the horizontal test cascade axis; positive when probe head is looking upwards against the flow.

dynvisc : Dynamic viscosity of air.

calcofl : $13.6 \times 9.81 \times (998.6/1000.)$; factor for converting from mmHg to Pa.

Testq : Will be used to determine whether low q or high q section of a particular calibration curve portion should be used.

```

iap1, iap2,
inp3      : Zero readings from the pressure transducers connected to
           the three hole probe.

rup1, rup2,
rup3      : Static pressures obtained from the three hole-probe (v)
           (reference pressure is test section inlet static pressure)

p1, p2, p3 : Static pressures obtained from the three hole-probe (Pa)

psin      : test section inlet static pressure (Pa).

ps        : static pressure at the measurement point (obtained from the
           K1 vs. flow angle calibration curve).

q         : dynamic pressure at the measurement point

Velocity  : Velocity magnitude at the measurement point

incappd   : Zero reading from the transducer which measures the
           contraction pressure difference (v).

rwcappd   : Contraction pressure difference (v).

cappd     : Contraction pressure difference (Pascal).

entpd     : test rig entrance dynamic pressure (Pascal).

entvel    : test rig entrance velocity (m/sec)

}

const

contrc    : real = 0.595; { contraction factor, ratio of the
                           dynamic pressure at the cascade inlet to the
                           contraction pressure difference }

{ Transducer calibration coefficients (Pascal/mv) : }

calcofQ   : real = 1.375; { For contraction pressure difference }
calcofP1   : real = 1.373; { for P1 }
calcofP2   : real = 1.428; { for P2 }
calcofP3   : real = 1.400; { for P3 }

TN        : integer = 0; { waiting period between processing the raw data
                           of sequential measurement points }

(-----)

function eval(y : real ; array1 : coefmatrix ; maxdeg, n : integer ) : real;

( The information on the least square fitted curves are in the form of arrays
  rather than simple coefficients; this function is used to process those

```

```

arrays so that for a given x , the corresponding y value is extracted. )

var

  ib, ic, n12, k, l   : integer;
  dk, dkp1, dkp2      : real;

begin { beginning of function eval }

  ib := maxdeg + 1;
  ic := maxdeg + ib - 1;

  { evaluate n = 0, 1 as special cases }

  if (n = 0) then begin
    eval := arrayl[ic];
  end; { of the if statement }

  if (n = 1) then begin
    eval := arrayl[ic] + arrayl[ic+1]*(y-arrayl[1]);
  end; { of the if statement }

  if (n > 1) then begin
    dkp2 := arrayl[ic + n];
    dkp1 := arrayl[ic + n - 1] + (y - arrayl[n])*dkp2;
    n12 := n-2;
    if (n12 >= 1) then begin
      for l := 1 to n12 do begin
        k := l+n12-1;
        dk := arrayl[ic+k] + (y-arrayl[k+1])*dkp1 - arrayl[ib+k]*dkp2;
        dkp2 := dkp1;
        dkp1 := dk;
      end;
      eval := arrayl[ic] + (y-arrayl[1])*dkp1 - arrayl[ib]*dkp2;
    end;
  end;

  -----
begin { beginning of program datareduction }

{ identification of input and output files }

Writeln ( ' Reduction of the data obtained from the three-hole probe ');
Writeln ( ' measurements ');
Writeln ( ' ');
Writeln ( ' Contraction pressure difference had to be measured with transducer ');
Writeln ( ' Setra 52936 and the probe p1, p2 and p3 pressures with transducers ');
Writeln ( ' Rosemount 633, 591 and 567 respectively ');
Writeln ( ' If not, the transducer calibration coefficients used in this ');
Writeln ( ' program have to be changed ! ');
Writeln ( ' ');
Writeln ( ' Enter the input file name which includes the coefficients of the ');

```

```

Write (' calibration curve polynomials fitted by least-square method : ');
Readln (infile2);
Writeln (' Enter the input file name for the array of the polynomial');
Write (' fitted by least-square method to the Ptot & Q calibration data : ');
Readln (infile3);
Clrscr;

```

```

Assign (infile2,infil2);
Reset (infile2);
for I := 1 to 21 do
  Readln (infile2,maxdeg[I],n[I]);
for I := 1 to 21 do begin
  for J := 1 to 200 do
    Readln (infile2,matrix[I,J]);
  end;
Close (infile2);

```

```

Assign (infile3,infil3);
Reset (infile3);
  Readln (infile3,maxptot,nptot);
  for J := 1 to 200 do
    Readln (infile3,arrayptot[J]);
Close (infile3);

```

```

repeat
  Clrscr;
  Writeln (' ');
  Write (' Enter the input file name which includes the measurements ');
  Readln (infile1);
  Writeln (' ');
  Write (' Enter output file name for measured raw data : ');
  Readln (outfil1);
  Write (' Enter first output file name for processed data ');
  Readln (outfil2);
  Write (' Enter second output file name for processed data : ');
  Readln (outfil3);
  Writeln (' Enter output file name for the data that will be used for ');
  Write (' input to the mass flow rate calculation program : ');
  Readln (outfil7);
  ClrScr;

```

```

Assign (infile1,infil1);
Reset (infile1);

```

(total temperature in °F , alpha in degrees, co-ordinates in mm., atmospheric pressure in mmHg, all other variables in volts.
 (For the definition of these variables refer to the data declaration section of the program))

```

Readln (infile1,tdate);
Readln (infile1,nofpoin,tipcir);
for I := 1 to nofpoin do
  Readln (infile1, x[I], y[I], z[I], rwatnprs[I], tottemp[I],alpha[I]);
for I := 1 to nofpoin do begin

```

```

Readln (infile1, inp1[I], rwp1[I], inp2[I], rwp2[I], inp3[I], rwp3[I],
        incmppd[I], rwcnpd[I]);
inp1[I] := inp1[I]*1000.0; inp2[I] := inp2[I]*1000.0; inp3[I] := inp3[I]*1000.0;
rwp1[I] := rwp1[I]*1000.0; rwp2[I] := rwp2[I]*1000.0; rwp3[I] := rwp3[I]*1000.0;
incmppd[I] := incmppd[I]*1000.0; rwcnpd[I] := rwcnpd[I]*1000.0;
end;
Close(infile1);

for I := 1 to nofpoin do begin
    tottemp[I] := (tottemp[I] - 32.0)/1.8 + 273.16;

    calcof1 := 13.6*9.81*998.6/1000.0;

    { The error of 0.7 mmHg in the barometer reading is taken into account }

    atmprs[I] := (rwatprs[I] - 0.7)*calcof1;

    { Convert contraction pressure difference into Pascal }

    cmppd[I] := (rwcnpd[I]-incmppd[I])*calcofQ;

    { Calculate the test rig entrance dynamic pressure using the
      contraction factor }

    entpd[I] := cmppd[I]*contrc;

    { Calculate the static temperature at the test cascade inlet : }

    stctemp[I] := tottemp[I]/( 1.0 +((0.4/1.4)*entpd[I]/atmprs[I] ));

    { Calculate the total pressure at the contraction
      ( it is within 1% of the test section inlet total pressure ) }

    Ptotcomp := eval(cmppd[I],arrayptot,maxptot,nptot) + atmprs[I];

    { calculate the test section inlet static pressure : }

    psin[I] := Ptotcomp - entpd[I];

    { calculate the density of the air flow at test rig entrance (Kg/m3) }

    densinlet := psin[I]/(287.0*stctemp[I]);

    { Calculate the dynamic viscosity of the air (N.sec/m2) at test rig
      entrance using Sutherland's approximate formula :
      ( 1.71E-05 is taken as dynamic air viscosity at 0.0 °C ) }

    dynvisc := 1.71E-05*(exp(1.5*ln(stctemp[I]/273.16)))*383.71556/
        ( stctemp[I] + 7199.0/1.8);

    { Calculate the velocity at test rig entrance : }

    entvel[I] := sqrt (entpd[I]*2.0/densinlet);

```

```
{ Calculate the Reynolds number based on chord length and test rig entrance velocity :}
```

```
Re[I] := densinlet*entvel[I]*0.250/dynvisc;
```

```
{ Convert the probe pressures p1, p2 and p3 (reference is the inlet static pressure ) into Pascal }
```

```
p1[I] := (rup1[I] - inp1[I])*calcofP1;
```

```
p2[I] := (rup2[I] - inp2[I])*calcofP2;
```

```
p3[I] := (rup3[I] - inp3[I])*calcofP3;
```

```
{ Calculate the coefficients KPS2 and KPS3 : }
```

```
If ( p1[I] <> p3[I] ) then
```

```
    kpsi2 := (p1[I] - p2[I])/(p1[I] - p3[I]);
```

```
If ( kpsi2 <> 0.0 ) then
```

```
    kpsi3 := 1./kpsi2;
```

```
    Sound (800);
```

```
    Delay (TN);
```

```
    Sound (500);
```

```
    Delay (TN);
```

```
    Nosound;
```

```
If ( I > 1 ) then begin
```

```
    Writeln(' ');
```

```
    Writeln(' ');
```

```
    Writeln(' ');
```

```
    Writeln ( ' Press any key to continue ...' );
```

```
    Repeat
```

```
    Until KeyPressed;
```

```
    Clrscr;
```

```
end;
```

```
{ CALCULATE THE FLOW ANGLE RELATIVE TO THE PROBE AXIS }
```

```
If (p2[I] < p3[I]) then begin
```

```
{ Psi is positive since the static pressure at 3 is  
larger than the one at 2 (for p2 = p3 psi will be 0) }
```

```
chpos := false;
```

```
Writeln ( ' ');
```

```
Writeln ( ' For point ',I:2, ' p3 > p2 => Psi is positive ' );
```

```
Writeln ( ' ');
```

```
Writeln ( ' x = ',x[I]:5:2, ' y = ',y[I]:5:2, ' z = ',z[I]:5:2,  
(in mm.) ' );
```

```
If (kpsi2 >= -0.97942) and (kpsi2 <= -0.04968) then begin
```

```
    chpos := true;
```



```

{ 48.0 <= Psi <= 70.0 }

Writeln(' ');
Writeln(' ');
Writeln('Psi is obtained from kpsi2 part 2');

L := 19;
for J := 1 to 200 do
  array1[J] := matrix[L,J];
  psi[I] := eval(kpsi2,array1,maxdeg[L],n[L]);
end;
If (kpsi3 <= 0.97308) and (kpsi3 > -1.02101) then begin
  chpos := true;

  { 0.0 <= Psi < 48.0 }

  Writeln(' ');
  Writeln(' ');
  Writeln('Psi is obtained from kpsi3 part 2');

  L := 21;
  for J := 1 to 200 do
    array1[J] := matrix[L,J];
    psi[I] := eval(kpsi3,array1,maxdeg[L],n[L]);
  end;
  If ( chpos = false ) then begin

    Writeln(' ');
    Writeln(' p1:=',p1[I]:6:2, ' p2:=',p2[I]:6:2, ' p3:=',p3[I]:6:2);
    Write -(' Is the point out of range ( psi > 70.0 ) (Y/N) ? ');
    repeat
      Readln(ansrep);
    until ansrep in ['Y', 'y', 'N', 'n'];
    If ( ansrep in ['Y', 'y'] ) then begin { Psi > 70 }

      Writeln(' ');
      Writeln(' kpsi2 is out of range (psi > 70.), extrapolation will');
      Writeln(' be used ');

      L := 19;
      for J := 1 to 200 do
        array1[J] := matrix[L,J];
        psi[I] := eval(kpsi2,array1,maxdeg[L],n[L]);
      end
    else begin { Psi = 0.0 - epsilon }

      L := 18;
      for J := 1 to 200 do
        array1[J] := matrix[L,J];
        psi[I] := eval(kpsi2,array1,maxdeg[L],n[L]);
      end;
    end;
  end;
end
end

```

```

else
begin
  { Psi is negative since p3 is smaller than p2 }
  chneg := false;

  Writeln ( ' ');
  Writeln ( ' ');
  Writeln ( ' For point ', I:2, ' Psi is negative ');
  Writeln ( ' ');
  Writeln ( ' x = ', x[I]:5:2, ' y = ', y[I]:5:2, ' z = ', z[I]:5:2,
    (in mm.)');

  If (kpsi2 >= -1.06480) and (kpsi2 < 1.02766) then begin
    chneg := true;

    { -47.0 <= Psi < 0.0 }

    Writeln ( ' ');
    Writeln ( ' ');
    Writeln ( ' Psi is obtained from kpsi2 part 1');

    L := 18;
    for J := 1 to 200 do
      array1[J] := matrix[L,J];
    psi[I] := eval(kpsi2,array1,maxdeg[L],n[L]);
  end;

  If ( kpsi3 <= 0.82784) and (kpsi3 > -0.93914) then begin
    chneg := true;

    { -70 <= Psi < -47 }

    Writeln ( ' ');
    Writeln ( ' ');
    Writeln ( ' Psi is obtained from kpsi3 part 1');

    L := 20;
    for J := 1 to 200 do
      array1[J] := matrix[L,J];
    psi[I] := eval(kpsi3,array1,maxdeg[L],n[L]);
  end;

  If ( chneg = false ) then begin

    Writeln ( ' ');
    Writeln ( ' p1=', p1[I]:6:2, ' p2=', p2[I]:6:2, ' p3=', p3[I]:6:2);
    Write ( ' Is the point out of range (psi < -70) (Y/N) ?');
    repeat
      readln(ansrep);
    until ansrep in ['y', 'n', 'Y', 'N'];
    If ( ansrep in ['y', 'Y'] ) then begin

      Writeln ( ' ');
      Writeln ( ' kpsi3 is out of range ( psi < -70.), extrapolation will');
      Writeln ( ' be used ');
    end;
  end;
end;

```

```

      L := 20;
      for J := 1 to 200 do
        array1[J] := matrix[L,J];
        psi[I] := eval(kpsi3,array1,maxdeg[L],n[L]);
      end
    else begin { Psi = 0.0 + epsilon }

      L := 21;
      for J := 1 to 200 do
        array1[J] := matrix[L,J];
        psi[I] := eval(kpsi3,array1,maxdeg[L],n[L]);
      end;
    end;
  end;
end;

```

```

  Writeln (' ');
  Writeln (' Psi (deg.) = ',psi[I]:6:2);
  Writeln (' ');

```

```

  ( CALCULATE THE DYNAMIC PRESSURE 'q' : )

```

```

  If (psi[I] <= -50.0) then begin

```

```

    { First assuming that q is low : }
    Write (' q is calculated from k12 part 1');

```

```

      L := 8;
      for J := 1 to 200 do
        array1[J] := matrix[L,J];
        k12 := eval(psi[I],array1,maxdeg[L],n[L]);
        q[I] := (p1[I] - p2[I])/k12;

```

```

      Testq := q[I]/calcofQ;
      If (Testq > 700.0) then begin

```

```

        Writeln (' _ high flow rate. ');

```

```

        L := 11;
        for J := 1 to 200 do
          array1[J] := matrix[L,J];
          k12 := eval(psi[I],array1,maxdeg[L],n[L]);
          q[I] := (p1[I] - p2[I])/k12;

```

```

      end
    else

```

```

      Writeln (' _ low flow rate. ');
      If ( psi[I] < -70.0) then begin

```

```

        Writeln (' ');
        Writeln (' Psi < -70.0 deg. In the calculation of q extrapolation is used');
        end;
      end;

```

```

  If (psi[I] < -30.0) and (psi[I] > -50.0) then begin

```

Writeln (' q is calculated from K12 part 2.');

```

L := 9;
for J := 1 to 200 do
  array1[J] := matrix[L,J];
  k12 := eval(psi[I],array1,maxdeg[L],n[L]);
  q[I] := (p1[I] - p2[I])/k12;
end;

```

If (psi[I] > -10.0) and (psi[I] <= 0.0) then begin

Writeln (' q is calculated from K12 part 3.');

```

L := 10;
for J := 1 to 200 do
  array1[J] := matrix[L,J];
  k12 := eval(psi[I],array1,maxdeg[L],n[L]);
  q[I] := (p1[I] - p2[I])/k12;
end;

```

If (psi[I] < 10.0) and (psi[I] > 0.0) then begin

Writeln (' q is calculated from K13 part 1.');

```

L := 12;
for J := 1 to 200 do
  array1[J] := matrix[L,J];
  k13 := eval(psi[I],array1,maxdeg[L],n[L]);
  q[I] := (p1[I] - p3[I])/k13;
end;

```

If (psi[I] > 30.0) and (psi[I] < 50.0) then begin

Writeln (' q is calculated from K13 part 2.');

```

L := 13;
for J := 1 to 200 do
  array1[J] := matrix[L,J];
  k13 := eval(psi[I],array1,maxdeg[L],n[L]);
  q[I] := (p1[I] - p3[I])/k13;
end;

```

If (psi[I] >= 50.0) then begin

(First assuming that q is low :)

Write (' q is calculated from K13 part 3.');

```

L := 14;
for J := 1 to 200 do
  array1[J] := matrix[L,J];
  k13 := eval(psi[I],array1,maxdeg[L],n[L]);
  q[I] := (p1[I] - p3[I])/k13;

```

```

Testq := q[I]/calcofQ;

If (Testq > 700.0) then begin

  Writeln (' _ high flow rate. ');

  L := 15;
  for J := 1 to 200 do
    array1[J] := matrix[L,J];
    k13 := eval(psi[I],array1,maxdeg[L],n[L]);
    q[I] := (p1[I] - p3[I])/k13;
  end
else

  Writeln (' _ low flow rate. ');

  If (psi[I] > 70.0) then begin
    Writeln (' ');
    Writeln (' Psi > 70.0 deg. In the calculation of q extrapolation is used ');
    end;
  end;

If (psi[I] >= -30.0) and (psi[I] <= -10.0) then begin

  Writeln (' q is calculated from K23 part 1. ');

  L := 16;
  for J := 1 to 200 do
    array1[J] := matrix[L,J];
    k23 := eval(psi[I],array1,maxdeg[L],n[L]);
    q[I] := (p2[I] - p3[I])/k23;
  end;

If (psi[I] >= 10.0 ) and (psi[I] <= 30.0 ) then begin

  Writeln (' q is calculated from K23 part 2. ');

  L := 17;
  for J := 1 to 200 do
    array1[J] := matrix[L,J];
    k23 := eval(psi[I],array1,maxdeg[L],n[L]);
    q[I] := (p2[I] - p3[I])/k23;
  end;

  { CALCULATE THE STATIC PRESSURE AT EACH DATA POINT . }

  If (psi[I] <= -50.0) then begin

    Write (' Static p is calculated from K11 part 1 ');

    Testq := q[I]/calcofQ;

    If (Testq <= 700.0) then begin

```

```

      Writeln (' _ low flow rate. ');

      L := 1;
      for J := 1 to 200 do
        array1[J] := matrix[L,J];
        k11 := eval(psi[I],array1,maxdeg[L],n[L]);

      end
    else begin

      Writeln (' _ high flow rate. ');

      L := 6;
      for J := 1 to 200 do
        array1[J] := matrix[L,J];
        k11 := eval(psi[I],array1,maxdeg[L],n[L]);
      end;
      If ( psi[I] < -70.0) then begin
        Writeln (' ');
        Writeln (' Psi < -70.0 deg. In the calculation of ps extrapolation is used');
      end;
    end;

    If(psi[I] > -50.0) and (psi[I] <= -15.0) then begin

      Writeln (' Static p is calculated from K11 part 2. ');

      L := 2;
      for J := 1 to 200 do
        array1[J] := matrix[L,J];
        k11 := eval(psi[I],array1,maxdeg[L],n[L]);
      end;

      If(psi[I] > -15.0) and (psi[I] < 15.0) then begin—

        Writeln (' Static p is calculated from K11 part 3. ');

        L := 3;
        for J := 1 to 200 do
          array1[J] := matrix[L,J];
          k11 := eval(psi[I],array1,maxdeg[L],n[L]);
        end;

        If(psi[I] >= 15.0) and (psi[I] < 50.0) then begin

          Writeln (' Static p is calculated from K11 part 4. ');

          L := 4;
          for J := 1 to 200 do
            array1[J] := matrix[L,J];
            k11 := eval(psi[I],array1,maxdeg[L],n[L]);
          end;

          If(psi[I] > 50.0) then begin

```

```

Write ( ' Static p is calculated from k11 part 5' );

Testq := q[I]/calcofQ;

If (Testq <= 700.0) then begin
  Writeln ( ' _ low flow rate.' );

  L := 5;
  for J := 1 to 200 do
    array1[J] := matrix(L,J);
    k11 := eval(psi[I],array1,maxdeg[L],n[L]);
  end
else begin

  Writeln ( ' _ high flow rate.' );

  L := 7;
  for J := 1 to 200 do
    array1[J] := matrix(L,J);
    k11 := eval(psi[I],array1,maxdeg[L],n[L]);
  end;
  If ( psi[I] > 70.0) then begin
    Writeln ( ' ');
    Writeln ( ' Psi > 70.0 deg. In the calculation of ps extrapolation is used' );
  end;
end;

ps[I] := -q[I]*k11 + p1[I];

{ Since p1 is relative to inlet static pressure, the above calculated
static pressure has also the same reference. Therefore absolute ps is }

ps[I] := ps[I] + psin[I];

{ Density at each data point : }

density[I] := ps[I]/(287.0*stctemp[I]);

{ Calculate the total pressure loss coefficient : }

LossPtot [I] := ( ( q[I] + ps[I] ) - Ptotcomp) /entpd[I];

{ Calculate the velocity at each data point ( nondimensionalized
by the test rig entrance velocity ) : }

If ( q[I] > 0.0 ) then begin
  velocity[I] := sqrt((q[I]*2.0)/density[I])/entvel[I];
end
else
begin
  Writeln ( ' ');
  Writeln ( ' q[I] is negative, possible reading error in the experiment.' );
  Writeln ( ' Velocity can not be calculated.' );

```

end;

```
{ Calculate the flow angle relative to x axis :
  alpha is positive when the three-hole probe head is looking upwards;
  Psi is positive when P3 is larger than P2,
  As a result, Beta is positive when the air flow is upwards relative
  to test rig horizontal axis}
```

```
Beta[I] := -(psi[I] + alpha[I]);
```

```
{ correct the raw atmospheric pressure reading for printing purpose }
```

```
rwatmprs[I] := rwatmprs[I] - 0.7 ;
```

end; { of the main loop }

```
Sound (800);
Delay (75);
Sound (500);
Delay (75);
Nosound;
Writeln(' ');
Writeln(' ');
Writeln(' ');
Writeln(' Press any key to continue ...');
Repeat until KeyPressed;
Clrscr;
```

```
{ write the raw data on a disk file : }
```

```
Assign (outfile1,outfil1);
Rewrite (outfile1);
Writeln (outfile1, ' Test Date : ',tdate);
Writeln (outfile1, ' ');
Writeln (outfile1, ' Tip clearance (t/c): ',tipclr:10:5);
Writeln (outfile1, ' ');
Writeln (outfile1, ' x, y and z location of three hole probe ');
Writeln (outfile1, ' ');
Writeln (outfile1, ' Alpha : angle between horizontal axis of test rig and the ');
Writeln (outfile1, ' three hole probe (positive when three hole probe ');
Writeln (outfile1, ' tip is looking upwards against the flow direction. ');
Writeln (outfile1, ' ');
Writeln (outfile1, ' ');
Writeln (outfile1, ' $      x (mm)      y (mm)      z (mm)      Alpha (deg.) ');
Writeln (outfile1, '-----');
Writeln (outfile1, ' ');
  for I := 1 to nofpoin do
Writeln (outfile1,I:3, ' ',x[I]:10:2, ' ',y[I]:10:2, ' ',z[I]:10:2, ' ',
          alpha[I]:10:3);
Writeln (outfile1, ' ');
Writeln (outfile1, ' ');
Writeln (outfile1, ' Pa : atm. pressure in mmHg. ');
Writeln (outfile1, ' ');
Writeln (outfile1, ' T (total) : total temperature (K)');
```



```

Writeln (outfile1, ' ');
Writeln (outfile1, ' $ T total (K) Pa (mmHg.) ');
Writeln (outfile1, '-----');
Writeln (outfile1, ' ');
for I := 1 to nofpoin do
Writeln (outfile1, I:3, ' ', tottemp[I]:10:2, ' ', rwatapsr[I]:10:3);
Writeln (outfile1, ' ');
Writeln (outfile1, ' Psc1-Psc2 : contraction pressure difference in mv. ');
Writeln (outfile1, ' ( initial reading not included ) ');
Writeln (outfile1, ' ');
Writeln (outfile1, ' Psc1-Psc2(in) : initial reading of contraction ');
Writeln (outfile1, ' pressure difference in mv. ');
Writeln (outfile1, ' ');
Writeln (outfile1, ' $ Psc1-Psc2(in) Psc1-Psc2 ');
Writeln (outfile1, '-----');
for I := 1 to nofpoin do
Writeln (outfile1, I:3, incmppd[I]:10:2, ' ', rucmppd[I]:10:2);
Writeln (outfile1, ' ');
Writeln (outfile1, ' ');
Writeln (outfile1, ' p1, p2 and p3 : three-hole probe measurements in mv. ');
Writeln (outfile1, ' ( initial reading not included ) ');
Writeln (outfile1, ' ');
Writeln (outfile1, ' inp : initial reading in mv. ');
Writeln (outfile1, ' ');
Writeln (outfile1, ' $ inp1 p1 - psin inp2 p2 - psin inp3 p3 - psin ');

Writeln
(outfile1, '-----');
for I := 1 to nofpoin do begin
Writeln (outfile1, I:3, ' ', inp1[I]:10:2, ' ', rwpl[I]:10:2,
        ' ', inp2[I]:10:2, ' ', rwpl2[I]:10:2,
        ' ', inp3[I]:10:2, ' ', rwpl3[I]:10:2);
end;
Close (outfile1);

{ Writing the processed data in a disk file :}

Assign (outfile2, outfile2);
Rewrite (outfile2);
Writeln (outfile2, ' Test Date ', tdate);
Writeln (outfile2, ' ');
Writeln (outfile2, ' Tip clearance (t/c): ', tipclr:10:5);
Writeln (outfile2, ' ');
Writeln (outfile2, ' x, y and z location of three hole probe ');
Writeln (outfile2, ' ');
Writeln (outfile2, ' Alpha : angle between horizontal axis of test rig and the ');
Writeln (outfile2, ' three hole probe (positive when three hole probe ');
Writeln (outfile2, ' tip is looking upwards and is located against the ');
Writeln (outfile2, ' flow direction) ');
Writeln (outfile2, ' Psi : angle between flow direction and the probe axis ');
Writeln (outfile2, ' (see corresponding text for sign convention) ');
Writeln (outfile2, ' ');
Writeln (outfile2, ' $ x (mm) y (mm) z (mm) Alpha (deg.) Psi (deg.) ');

```

```

Writeln (outfile2, '-----');
Writeln (outfile2, ' ');
for I := 1 to nfpoin do
Writeln (outfile2, I:3, x[I]:10:2, ' ', y[I]:10:2, ' ',
          z[I]:10:2, ' ', alpha[I]:10:3, ' ', psi[I]:10:3);
Writeln (outfile2, ' ');
Writeln (outfile2, 'T (static) : Static temperature at test rig entrance (K) ');
Writeln (outfile2, ' ');
Writeln (outfile2, 'q-ent : Test rig entrance d. pressure (Pa) ');
Writeln (outfile2, ' ');
Writeln (outfile2, 'V-ent : Test rig entrance velocity (m/sec) ');
Writeln (outfile2, ' ');
Writeln (outfile2, 'T (static) (K)      Patm (Pa)      q-ent      V-ent ');
Writeln (outfile2, '-----');
Writeln (outfile2, ' ');
for I := 1 to nfpoin do
Writeln (outfile2, I:3, ' ', stctemp[I]:10:2, ' ', atmprs[I]:10:3, ' ',
          entpd[I]:8:3, ' ', entvel[I]:9:2 );
Writeln (outfile2, ' ');
Writeln (outfile2, 'p1, p2 and p3 : three-hole probe measurements in Pa. ');
Writeln (outfile2, ' ');
Writeln (outfile2, 'p1 - Psin      p2 - Psin      p3 - Psin ');
Writeln (outfile2, '-----');
for I := 1 to nfpoin do
Writeln (outfile2, I:3, ' ', p1[I]:10:5, ' ', p2[I]:10:5, ' ', p3[I]:10:5);
Close (outfile2);

( write the result of data reduction in a disk file )

Assign (outfile3, outfil3);
Rewrite (outfile3);
Writeln (outfile3, 'Test Date ', tdate);
Writeln (outfile3, ' ');
Writeln (outfile3, 'Tip clearance (t/c): ', tipclr:10:5);
Writeln (outfile3, ' ');
Writeln (outfile3, 'x, y and z location of three hole probe ');
Writeln (outfile3, ' ');
Writeln (outfile3, 'x (mm)      y (mm)      z (tg) ');
Writeln (outfile3, '-----');
Writeln (outfile3, ' ');
for I := 1 to nfpoin do
Writeln (outfile3, I:3, ' ', x[I]:10:3, ' ', y[I]:10:3, ' ',
          z[I]:10:3);
Writeln (outfile3, ' ');
Writeln (outfile3, 'Ps-ent : Static pressure at test rig entrance ');
Writeln (outfile3, ' ');
Writeln (outfile3, 'T (static) : Static temperature at test rig entrance (K) ');
Writeln (outfile3, ' ');
Writeln (outfile3, 'Beta : Flow direction relative to the horizontal axis ');
Writeln (outfile3, 'of the test rig. Positive when air flows upwards. ');
Writeln (outfile3, ' ');
Writeln (outfile3, 'Re : Reynolds number based on chord length and test rig ');
Writeln (outfile3, 'entrance velocity. ');
Writeln (outfile3, ' ');

```

```

Writeln (outfile3, ' # T (static)(I) Ps-ent (Pa.) Beta (deg.) Re ');
Writeln (outfile3, '-----');
Writeln (outfile3, ' ');
  for I := 1 to nofpoin do
Writeln (outfile3, I:3, ' ', stctemp[I]:10:2, ' ', psin[I]:10:3,
          ' ', Beta[I]:10:3, ' ', Re[I]:10:3);
Writeln (outfile3, ' ');
Writeln (outfile3, ' q : Dynamic pressure at the data point (Pa).');
Writeln (outfile3, ' ');
Writeln (outfile3, ' V : Velocity at the data point (nondimensionalized');
Writeln (outfile3, ' by the test rig entrance velocity).');
Writeln (outfile3, ' ');
Writeln (outfile3, ' Ps : Static pressure at the data point (Pa).');
Writeln (outfile3, ' ');
Writeln (outfile3, ' Density : Density at the data point (kg/m3).');
Writeln (outfile3, ' ');
Writeln (outfile3, ' LossPtot : Total pressure loss coef. at the data point ');
Writeln (outfile3, ' ( Ptot - Ptot(inlet) )/ q(inlet) ');
Writeln (outfile3, ' ');
Writeln (outfile3, ' # q (Pa.) V Ps Density LossPtot');
Writeln (outfile3, '-----');
Writeln (outfile3, ' ');
  for I := 1 to nofpoin do
Writeln (outfile3, I:3, ' ', q[I]:10:3, ' ', velocity[I]:8:3,
          ' ', ps[I]:14:3, ' ', density[I]:10:7, ' ', LossPtot[I]:10:7);
Close (outfile3);

Assign ( outfile7, outfil7);
Rewrite (outfile7);
  for I := 1 to nofpoin do
Writeln (outfile7, x[I]:10:3, y[I]:10:3, z[I]:10:3, velocity[I]:10:7,
          density[I]:10:8, q[I]:15:12);
Close (outfile7);

{ write plotting data on disk files :}
Clrscr;
Writeln ( ' ');
Write ( ' Enter output file name for co-ordinates ');
Readln (outfil4);
Write ( ' Enter output file name for velocity : ');
Readln (outfil5);
Write ( ' Enter output file name for flow angle : ');
Readln (outfil6);
Write ( ' Enter output file name for Ptot ');
Readln (outfil8);

Writeln ( ' ');
Writeln ( ' Press any key when ready ...');
Repeat until Keypressed;

Assign (outfile4, outfil4);
Rewrite (outfile4);
  for I := 1 to nofpoin do

```

```

Writeln (outfile4,z[I]:10:2);
Close (outfile4);

Assign (outfile5,outfil5);
Rewrite (outfile5);
  for I := 1 to nofpoin do
Writeln (outfile5,velocity[I]:9:3);
Close (outfile5);

Assign (outfile6,outfil6);
Rewrite (outfile6);
  for I := 1 to nofpoin do
Writeln (outfile6,Beta[I]:10:3);
Close (outfile6);

Assign (outfile8,outfil8);
Rewrite (outfile8);
  for I := 1 to nofpoin do
Writeln (outfile8,LossPtot[I]:10:7);
Close (outfile8);

repeat
Writeln (' ');
Write (' Do you want to run the program again (Y/N) ? ');
Readln (ansrep);
until ansrep in ['n','N','y','Y'];

until ansrep in ['n','N'];

end. ( of program datareduction )

```

APPENDIX D**Transducer Calibration Curves**

- Fig. D.1 Transducer Rosemount 567 Calibration Curve
- Fig. D.2 Transducer Rosemount 591 Calibration Curve
- Fig. D.3 Transducer Rosemount 633 Calibration Curve
- Fig. D.4 Transducer Rosemount 557 Calibration Curve
- Fig. D.5 Transducer Setra 52935 Calibration Curve
- Fig. D.6 Transducer Setra 52936 Calibration Curve

Fig. D.1 Transducer Rosemount 567 Calibration Curve

Fig. D.2 Transducer Rosemount 591 Calibration Curve

Fig. D.3 Transducer Rosemount 633 Calibration Curve

Fig. D.4 ROSEMOUNT 557 TRANSDUCER CALIBRATION

Fig. D.5 SETRA 52935 TRANSDUCER CALIBRATION

Fig. D.6 SETRA 52936 TRANSDUCER CALIBRATION

APPENDIX E

Data Acquisition Programs

- E.1 Program for blade surface static pressure measurements using the Taurus data acquisition board
- E.2 Program for endwall static pressure measurements using the Taurus data acquisition board
- E.3 Program for three-hole probe measurements using the Taurus data acquisition board
- E.4 Program for blade surface static pressure measurements using the HP data acquisition system
- E.5 Program for endwall static pressure measurements using the HP data acquisition system
- E.6 Program for three-hole probe measurements using the HP data acquisition system

(The programs have been coded in GWBasic and are to be run on an IBM compatible micro computer)

E .1

[illegible]


```

2150 LOCATE 22,35 : PRINT " STEP 2 "
2160 COUNTERX = 0
2170 IF(ANSW$ = "Y") OR (ANSW$ = "y") THEN PORTX(IX)=0 : GOTO 1720 ELSE FIN2X = 1 : GOTO 1980
2180
2190 LOCATE 16,20 : INPUT " IS THE TAPE ON THE BLADE CHANGED ? ", ANS$
2200 IF ( ANS$ = "y" ) OR (ANS$ = "Y") THEN LOCATE 16,20 : PRINT "

```

[illegible]

E.2

[illegible]

```

530 PRINT
540 PRINT "Enter the calibration coefficient of the transducer"
550 INPUT "used for the endwall pressure measurement (Pa/mv): ", CALB2
560 CLS
570
580 K1X = IN1X : K2X = INJX
590 I1X = IN1X : J1X = INJX
600
610 READING THE NUMBER OF TAPS ON EACH COLUMN OF THE GRID
620
630 FOR KX = 1 TO 17
640 READ FX(KX)
650 NEXT KX
660 DATA 11 ,11 ,13 ,13 ,14 ,14 ,13 ,14 ,14 ,14 ,14 ,13 ,13 ,13 ,13 ,13 ,13
670
680
690 WRITING THE INITIAL INFORMATION INTO OUTPUT FILES
700
710 IF (ANW$ = "Y") OR ( ANW$ = "y" ) THEN GOTO 1110
720 OPEN FAN$ FOR APPEND AS #2
730 PRINT#2, " TEST DATE : "; TDATE$
740 PRINT#2, " "
750 PRINT#2, " TIP CLEARANCE (t/c) : "; CLRN
760 PRINT#2, " "
770 PRINT#2, " WAITING PERIOD BEFORE TAKING DATA (SEC): "; USING "##.0"; WSEC
780 PRINT#2, " "
790 PRINT#2, " SAMPLING PERIOD (SEC) : "; USING "##.0"; AVSEC
800 PRINT#2, " "
810 PRINT#2, " TRANSDUCER CALIBRATION COEFFICIENTS : "
820 PRINT#2, " FOR Psc1-Psc2 : "; USING "###.####"; CALB1
830 PRINT#2, " FOR Ps(endwall) - Ps (inlet) : "; USING "###.####"; CALB2
840 PRINT#2, " "
850 PRINT#2, " INITIAL TRANSDUCER READINGS (Volts) AT THE BEGINNING OF THE EXP. "
860 PRINT#2, " Psc1 - Psc2 : "; USING "+###.#####"; IN1
870 PRINT#2, " Ps(endwall) - Ps (inlet) : "; USING "+###.#####"; IN2
880 PRINT#2, " "
890 PRINT#2, " TOTAL TEMPERATURE AT THE BEGINNING OF THE EXP (IN F ) : TOTTMP
900 PRINT#2, " "
910 PRINT#2, " ATMOSPHERIC PRESSURE AT THE BEGINNING OF THE EXP. (mm Hg) : ; ATHPRS
920 PRINT#2, " "
930 PRINT#2, "      #   PORT #   CLN #   ROW #   Psc1 - Psc2 (V)       P-Ps (V) "
940 PRINT#2, " -----"
950 PRINT#2, " "
960 CLOSE 2
970 OPEN FAN2$ FOR APPEND AS #3
980 PRINT#3, " TEST DATE : "; TDATE$
990 PRINT#3, " "
1000 PRINT#3, " TIP CLEARANCE (t/c) : "; CLRN
1010 PRINT#3, " "
1020 PRINT#3, " WAITING PERIOD BEFORE TAKING DATA (SEC): "; USING "##.0"; WSEC
1030 PRINT#3, " "
1040 PRINT#3, " SAMPLING PERIOD (SEC) : "; USING "##.0"; AVSEC
1050 PRINT#3, " "
1060 PRINT#3, "      #   CLN #   ROW #   Cp

```



```

1610
1620      LOCATE 22,16 : PRINT RIGHT$(TIME$,2)
1630
1640  CALCULATING Cp FROM THE SAMPLED DATA
1650
1660      ASUM1 = 0! : ASUM2 = 0! : CPSUM = 0!
1670      Q(IIX+1) = Q(IIX)
1680      FOR ZX = 1 TO IIX
1690          CPSUM = CPSUM + ((PS(ZX)-IN2)*CALB2)/((Q(ZX)+Q(ZX+1))/2!)-IN1)*CALB1*CONTRC)
1700
1710          ASUM1 = ASUM1 + Q(ZX)
1720          ASUM2 = ASUM2 + PS(ZX)
1730      NEXT ZX
1740  AVERAGING THE RECORDED DATA
1750
1760      AVER1(IX,JX) = ASUM1/(IIX)
1770      AVER2(IX,JX) = ASUM2/(IIX)
1780      CP(IX,JX) = CPSUM/(IIX)
1790
1800  PRINT THE RESULTS ON THE SCREEN
1810
1820      LOCATE 5,3 : PRINT IIX
1830      LOCATE 5,20 : PRINT USING "###.#####"; AVER1(IX,JX)
1840      LOCATE 12,3 : PRINT IIX
1850      LOCATE 12,20 : PRINT USING "###.#####"; AVER2(IX,JX)
1860
1870      K4X = IX
1880      K3X = JX
1890  COUNTERX IS USED TO DETERMINE WHEN TO SEND THE DATA TO DISK FILE
1900      COUNTERX = COUNTERX+1
1910      IF (COUNTERX > 15 ) GOTO 2380
1920  STEP THE SCANIVALVE
1930      VALUEX = 1
1940      CALL TAURUS (TOUT$,DOS$,DOUT$,VALUEX,ERRCODX)
1950      VALUEX = 0
1960      CALL TAURUS (TOUT$,DOS$,DOUT$,VALUEX,ERRCODX)
1970      IF ERRCODX < 0 THEN GOSUB 2930
1980
1990      PTENPX = PORTX(IX,JX)
2000      IIX = 0
2010      JX = JX+1
2020      IF ( JX > FX(IX) ) THEN IX = IX + 1 : JX = 1
2030      IF ( IX > 17 ) THEN GOTO 2380
2040
2050  IF(PTENPX < 47 ) THEN PORTX(IX,JX) = PTENPX + 1 ELSE GOTO 2850
2060      FOR IX = 1 TO 900
2070          NEXT IX
2080
2090  PREPARING THE SCREEN FOR THE NEXT MEASUREMENT CYCLE
2100
2110      LOCATE-12,3 : PRINT " " : LOCATE 5,3 : PRINT " "
2120      LOCATE 22,16 : PRINT " " : LOCATE 12,20 : PRINT " "
2130      LOCATE 5,20 : PRINT " "
2140

```

```

2150 CNTX = CNTX + 1
2160 IF ( CNTX = 10 ) THEN GOSUB 2750
2170
2180 TIMES = "00:00:00"
2190 RETURNING TO THE BEGINNING
2200 GOTO 1510
2210
2220 IIX = IIX + 1
2230 ++++++++ READ ANALOG INPUT 1 ++++++++
2240
2250 CALL TAURUS (TINP$,AIS,LAINIX,Q(IIX),ERRCODX)
2260 IF ERRCODX < 0 THEN GOSUB 2930
2270 LOCATE 5,3 : PRINT IIX
2280 LOCATE 5,20 : PRINT USING "###.#####"; Q(IIX)
2290
2300 ++++++++ READ ANALOG INPUT 2 ++++++++
2310
2320 CALL TAURUS (TINP$,AIS,LAIN2X,PS(IIX),ERRCODX)
2330 IF ERRCODX < 0 THEN GOSUB 2930
2340 LOCATE 12,3 : PRINT IIX
2350 LOCATE 12,20 : PRINT USING "###.#####"; PS(IIX)
2360 GOTO 1570
2370
2380 ((((((((((( ARCHIVE )))))))))))
2390
2400 COUNTRYX = 1
2410 OPEN FANEX FOR APPEND AS #2
2420
2430 FOR IPRX = K1X TO K4X
2440 IF( IPRX = K4X ) THEN JLINX = K3X ELSE JLINX = FX(IPRX)
2450 IF( IPRX = K1X ) THEN JFINX = K2X ELSE JFINX = 1
2460 FOR JPRX = JFINX TO JLINX
2470 PRINT#2, USING "####.8"; JJX; PORTX(IPRX,JPRX);
2480 PRINT#2, USING "#####.8"; IPRX;
2490 PRINT#2, USING "#####.8"; JPRX;
2500 PRINT#2, USING "+#####.####"; AVER1(IPRX,JPRX);
2510 PRINT#2, USING "+#####.####"; AVER2(IPRX,JPRX)
2520 JJX = JJX + 1
2530 NEXT JPRX
2540 NEXT IPRX
2550 CLOSE 2
2560
2570 OPEN FANEX2 FOR APPEND AS #3
2580 FOR IPRX = K1X TO K4X
2590 IF( IPRX = K4X ) THEN JLINX = K3X ELSE JLINX = FX(IPRX)
2600 IF( IPRX = K1X ) THEN JFINX = K2X ELSE JFINX = 1
2610 FOR JPRX = JFINX TO JLINX
2620 PRINT#3, USING "###.8"; STPX;
2630 PRINT#3, " ";
2640 PRINT#3, USING "###.8"; IPRX;
2650 PRINT#3, " ";
2660 PRINT#3, USING "###.8"; JPRX;
2670 PRINT#3, USING "#####.#####"; CP(IPRX, JPRX)
2680 STPX = STPX + 1

```


[illegible]


```

1070      LOCATE 22,8 : PRINT "SECONDS : "
1080      LOCATE 15,8 : PRINT "STATION # : "
1090
1100      INITIALIZING THE REAL TIME CLOCK
1110
1120      TIME$ = "00:00:00"
1130      IIX = 0
1140      LOCATE 15,17 : PRINT USING "###" ; IIX
1150      IF (VAL(RIGHT$(TIME$,2)) = 0 ) THEN LOCATE 18,16 : PRINT "WAITING"
1160      IF (VAL(RIGHT$(TIME$,2)) < WSEC ) THEN GOTO 1140
1170      IF (VAL(RIGHT$(TIME$,2)) = WSEC ) THEN LOCATE 18,16 : PRINT "
1180
1190
1200
1210      IF ( VAL(RIGHT$(TIME$,2)) = TOTSEC ) THEN GOTO 1460
1220      IIX = IIX + 1
1230
1240      ++++++ READ ANALOG INPUT ( Psc1-Psc2 ) ++++++
1250
1260      CALL TAURUS (TINP$,AI$,LAINQX,Q(IIX),ERRCODX)
1270      IF ERRCODX < 0 THEN GOSUB 2960
1280
1290      ++++++ READ ANALOG INPUT ( P1 ) ++++++
1300
1310      CALL TAURUS (TINP$,AI$,LAIN1X,PS1(IIX),ERRCODX)
1320      IF ERRCODX < 0 THEN GOSUB 2960
1330
1340      ++++++ READ ANALOG INPUT ( P2 ) ++++++
1350
1360      CALL TAURUS (TINP$,AI$,LAIN2X,PS2(IIX),ERRCODX)
1370      IF ERRCODX < 0 THEN GOSUB 2960
1380
1390      ++++++ READ ANALOG INPUT ( P3 ) ++++++
1400
1410      CALL TAURUS (TINP$,AI$,LAIN3X,PS3(IIX),ERRCODX)
1420      IF ERRCODX < 0 THEN GOSUB 2960
1430
1440      GOTO 1180
1450
1460      LOCATE 22,16 : PRINT RIGHT$(TIME$,2)
1470      ASUNQ = 0! : ASUN1 = 0! : ASUN2 = 0! : ASUN3 = 0!
1480      FOR ZX = 1 TO IIX
1490          ASUNQ = ASUNQ + Q(ZX)
1500          ASUN1 = ASUN1 + PS1(ZX)
1510          ASUN2 = ASUN2 + PS2(ZX)
1520          ASUN3 = ASUN3 + PS3(ZX)
1530      NEXT ZX
1540
1550      AVERAGING THE DATA RECORDED DURING THE SAMPLING PERIOD
1560
1570      AVERQ(IIX) = ASUNQ/(IIX)
1580      AVER1(IIX) = ASUN1/(IIX)
1590      AVER2(IIX) = ASUN2/(IIX)
1600      AVER3(IIX) = ASUN3/(IIX)

```

[illegible]

```

2150 PRINT#2, " SAMPLING PERIOD (SEC) : "; USING "##.9"; AVSEC
2160 PRINT#2, " "
2170 PRINT#2, " PROBE ANGLE RELATIVE TO TEST RIG HORIZONTAL AXIS : "; ALPHA
2180 PRINT#2, " "
2190 PRINT#2, "      X (mm)   Y (mm)   Z (mm)   Patn (mmHg)   Ttot (K)
2200 PRINT#2, "-----"
2210 PRINT#2, " "
2220       FOR JJX = 1 TO IX
2230 PRINT#2, USING "###.9"; JJX;
2240 PRINT#2, " ";
2250 PRINT#2, USING "+###.##"; XCO;
2260 PRINT#2, " ";
2270 PRINT#2, USING "+###.##"; YCO;
2280 PRINT#2, " ";
2290 PRINT#2, USING "+###.##"; ZCO(JJX);
2300 PRINT#2, " ";
2310 PRINT#2, USING "+###.##"; ATNPRS(JJX);
2320 PRINT#2, " ";
2330 PRINT#2, USING "+##.##"; TOTTHP(JJX)
2340     NEXT JJX
2350 PRINT#2, " "
2360 PRINT#2, "      INP   Psc1-Psc2   INP1       P1       INP2       P2       INP3       P3 "
2370 PRINT#2, "-----"
2380 PRINT#2, " "
2390       FOR JJX = 1 TO IX
2400 PRINT#2, USING "###"; JJX;
2410 PRINT#2, " ";
2420 PRINT#2, USING "+#.###"; INQ(JJX);
2430 PRINT#2, " ";
2440 PRINT#2, USING "+#.####"; AVERQ(JJX);
2450 PRINT#2, " ";
2460 PRINT#2, USING "+#.###"; IN1(JJX);
2470 PRINT#2, " ";
2480 PRINT#2, USING "+#.####"; AVER1(JJX);
2490 PRINT#2, " ";
2500 PRINT#2, USING "+#.###"; IN2(JJX);
2510 PRINT#2, " ";
2520 PRINT#2, USING "+#.####"; AVER2(JJX);
2530 PRINT#2, " ";
2540 PRINT#2, USING "+#.###"; IN3(JJX);
2550 PRINT#2, " ";
2560 PRINT#2, USING "+#.####"; AVER3(JJX)
2570     NEXT JJX
2580     CLOSE 2
2590     OPEN FAME2: FOR APPEND AS #3
2600 PRINT#3, YDATE$; " "; STN$
2610 PRINT#3, STX; " "; CLRN
2620     FOR JJX = 1 TO IX
2630 PRINT#3, USING "+###.##"; XCO;
2640 PRINT#3, " ";
2650 PRINT#3, USING "+###.##"; YCO;
2660 PRINT#3, " ";
2670 PRINT#3, USING "+###.##"; ZCO(JJX);
2680 PRINT#3, " ";

```


E 4

```

10 DATA ACQUISITION PROGRAM FOR BLADE SURFACE STATIC PRESSURE
20 MEASUREMENTS WITH THE HP DATA ACQUISITION SYSTEM
30
40 Set up program for MS-DOS HP-IB I/O Library
50 For use independent of the PC instrument bus system
60
70 DEF SEG
80 CLEAR ,&HFE00
90 I=&HFE00
100
110 PCIB.DIR$ represents the directory where the library files
120 are located
130 PCIB is an environment variable which should be set from MS-DOS
140 i.e. A:> SET PCIB=A:\LIB
150
160 If there is insufficient environment space a direct assignment
170 PRINT
180 PCIB.DIR$ = "A:\LIB"
190 Using the environment variable is the preferred method
200
210 PCIB.DIR$ = ENVIRON$("PCIB")
220 I$ = PCIB.DIR$ + "\PCIBILC.BLD"
230 BLOAD I$,&HFE00
240 CALL I(PCIB.DIR$, IX, JX)
250 PCIB.SEG = IX
260 IF JX=0 THEN GOTO 330
270 PRINT "Unable to load.";
280 PRINT " (Error #";JX;")"
290 STOP
300
310 Define entry points for setup routines
320
330 DEF SEG = PCIB.SEG
340 O.S = 5
350 C.S = 10
360 I.V = 15
370 I.C = 20
380 L.P = 25
390 LD.FILE = 30
400 GET.HEN = 35
410 L.S = 40
420 PANELS = 45
430
440 Establish error variables and ON ERROR branching
450
460 DEF.ERR = 50
470 PCIB.ERR$ = STRING$(64,32)
480 PCIB.NAME$ = STRING$(16,32)
490 CALL DEF.ERR(PCIB.ERR,PCIB.ERR$,PCIB.NAME$,PCIB.GLBERR)
500 PCIB.BASERR = 255
510 ON ERROR GOTO 830
520

```

```

530 J=-1
540 I$=PCIB.DIR$+"\\HP-IB.SYN"
550 CALL O.S(I$)
560 IF PCIB.ERR<>0 THEN ERROR PCIB.BASERR
570
580 Determine entry points for HP-IB Library routines
590
600 I=0
610 CALL I.V(I,IOABORT,IOCLEAR,IOCONTROL,IOENTER)
620 IF PCIB.ERR<>0 THEN ERROR PCIB.BASERR
630 CALL I.V(I,IOENTERA,IOENTERS,IOEOI,IOEOL)
640 IF PCIB.ERR<>0 THEN ERROR PCIB.BASERR
650 CALL I.V(I,IOGETTERM,IOLLOCKOUT,IOLLOCAL,IOMATCH)
660 IF PCIB.ERR<>0 THEN ERROR PCIB.BASERR
670 CALL I.V(I,IOOUTPUT,IOOUTPUTA,IOOUTPUTS,IOPOLL)
680 IF PCIB.ERR<>0 THEN ERROR PCIB.BASERR
690 CALL I.V(I,IOPOLLC,IOPOLLD,IORNOTE,IORSET)
700 IF PCIB.ERR<>0 THEN ERROR PCIB.BASERR
710 CALL I.V(I,IOSEND,IOSPOLL,IOSTATUS,IOTIMEOUT)
720 IF PCIB.ERR<>0 THEN ERROR PCIB.BASERR
730 CALL I.V(I,IOTRIGGER,J,J,J)
740 IF PCIB.ERR<>0 THEN ERROR PCIB.BASERR
750 CALL C.S
760 I$=PCIB.DIR$+"\\HP-IB.PLD"
770 CALL L.P(I$)
780 IF PCIB.ERR<>0 THEN ERROR PCIB.BASERR
790 GOTO 860
800
810 Error handling routine
820
830 IF ERR=PCIB.BASERR THEN GOTO 860
840 PRINT "BASIC error $";ERR;" occurred in line ";ERL
850 STOP
860 TMPERR = PCIB.ERR
870 IF TMPERR = 0 THEN TMPERR = PCIB.GLBERR
880 PRINT "PC Instrument error $";TMPERR;" detected at line ";ERL
890 PRINT "Error: ";PCIB.ERR$
900 STOP
910
920 COMMON declarations are needed if your program is going to chain
930 to other programs. When chaining, be sure to call DEF.ERR as
940 well upon entering the chained-to program
950
960 COMMON PCIB.DIR$,PCIB.SEG
970 COMMON LD.FILE,GET.NRN,PANELS,DEF.ERR
980 COMMON PCIB.BASERR,PCIB.ERR,PCIB.ERR$,PCIB.NAMES,PCIB.GLBERR
990 COMMON IOABORT,IOCLEAR,IOCONTROL,IOENTER,IOENTERA,IOENTERS,IOEOI,
IOEOL,IOGETTERM,IOLLOCKOUT,IOLLOCAL,IOMATCH,IOOUTPUT,IOOUTPUTA,
IOOUTPUTS,IOPOLL,IOPOLLC,IOPOLLD,IORNOTE,IORSET,IOSEND,IOSPOLL,
IOSTATUS,IOTIMEOUT,IOTRIGGER
1000
1010 FALSE = 0
1020 TRUE = NOT FALSE
1030 NOERR = 0

```

```

1040 UNKNOWN = 100001!
1050 ESEL = 100002!
1060 ERANGE = 100003!
1070 ETIME = 100004!
1080 ECTRL = 100005!
1090 EPASS = 100006!
1100 ENUM = 100007!
1110 EADDR = 100008!
1120 COMMON FALSE, TRUE, NOERR, UNKNOWN, ESEL, ERANGE, ETIME, ECTRL, EPASS, ENUM, EADDR
1130
1140
1150
1160
1170
1180
1190 CLS
1200 DIM AVER1(200), AVER2(200), FX(200), PORTX(200), CP(200)
1210 DIM Q(1000), PS(1000), READING(1000,2)
1220
1230
1240 SPECIFYING THE DEVICE ADDRESSES
1250 ISC = 7 : DAC = 709 : DVM = 722
1260 INITIALIZE THE DEVICES
1270
1280 RESETING THE HB INTERFACE CARD
1290 CALL IORESET (ISC)
1300 IF PCIB.ERR = 0! THEN GOTO 1330
1310 PRINT "ERROR IN INITIALIZING THE INTERFACE CARD : ";PCIB.ERR$ : STOP
1320
1330 CLEARING THE 3497A DATA ACQUISITION/CONTROL UNIT AND THE 3456A DVM
1340 CALL IOCLEAR (DAC)
1350 IF PCIB.ERR = 0! THEN GOTO 1370
1360 PRINT "ERROR IN CLEARING THE 3497A DAC SYSTEM : ";PCIB.ERR$ : STOP
1370 CALL IOCLEAR (DVM)
1380 IF PCIB.ERR = 0! THEN GOTO 1410
1390 PRINT "ERROR IN CLEARING THE 3456A DVM SYSTEM : ";PCIB.ERR$ : STOP
1400
1410 INITIALIZING SOME OF THE PARAMETERS THAT WILL BE USED IN THE PROGRAM
1420 FIN1% = 0 : FIN2% = 0
1430
1440 PRINT "SEND THE SCANIVALVE TO PORT 0"
1450 *** PERFORMING SELF TEST FOR DVM 3456A :
1460 PRINT "DVM 3456A SELF TEST IS PERFORMED : "
1470 SQ$ = "TE1" : L = LEN(SQ$)
1480 CALL IOOUTPUTS (DVM,SQ$,L)
1490 IF PCIB.ERR = 0 THEN GOTO 1510
1500 PRINT "ERROR IN 3456A SELF TEST : ";PCIB.ERR$ : STOP
1510 INPUT "PRESS RETURN TO COMPLETE DVM SELF TEST PROCEDURE : ";DUMMY
1520 SQ$ = "TE0" : L = LEN(SQ$)
1530 CALL IOOUTPUTS (DVM,SQ$,L)
1540 IF PCIB.ERR = 0 THEN GOTO 1560
1550 PRINT "ERROR IN 3456A SELF TEST : ";PCIB.ERR$ : STOP
1560 ***
1570

```



```

1580 *** PERFORMING SELF TEST FOR DAC 3497A :
1590 PRINT "DAC 3497A SELF TEST IS PERFORMED : "
1600 SQ$ = "ST1" : L = LEN(SQ$)
1610 CALL IOOUTPUTS (DAC,SQ$,L)
1620 IF PCIB.ERR = 0 THEN GOTO 1640
1630 PRINT "ERROR IN 3497A SELF TEST : ";PCIB.ERR$ : STOP
1640 INPUT "PRESS RETURN TO COMPLETE DVM SELF TEST PROCEDURE : ";DUMMY
1650 SQ$ = "ST0" : L = LEN(SQ$)
1660 CALL IOOUTPUTS (DAC,SQ$,L)
1670 IF PCIB.ERR = 0 THEN GOTO 1690
1680 PRINT "ERROR IN 3497A SELF TEST : ";PCIB.ERR$ : STOP
1690 ***
1700 PRINT
1710 PRINT "FLOW RATE MUST BE CONNECTED TO ANALOG CHANNEL # 4;"
1720 PRINT "Ps-Ps(inlet) MUST BE CONNECTED TO ANALOG CHANNEL # 5"
1730 INPUT "PRESS RETURN TO CONTINUE ... "; DUMMY : CLS
1740 PRINT
1750 INPUT "Do you want to continue to an existing data file (Y/N) ?", ANSW$
1760 PRINT
1770 PRINT "Enter the zero reading of the transducer used for "
1780 INPUT "contraction pressure difference (in volts): ", IN1
1790 PRINT
1800 PRINT "Enter the zero reading of the transducer used for "
1810 INPUT "blade surface pressure (in volts): ", IN2
1820 INPUT "Enter the initial scanivalve port number : ", PORTX(1)
1830 PRINT
1840 INPUT "Enter the output file name ( for raw data ) : ", FANEX$
1850 PRINT
1860 INPUT "Enter the output file name ( for cp distrb.) : ", FANEX2$
1870 PRINT
1880 PRINT "Enter row number on the blade ( 1 ... 14 ) "
1890 INPUT " ( row number increases towards the back wall ) : ", ROWX
1900 CLS
1910 PRINT
1920 PRINT "Enter the tab number that is connected to the initial"
1930 INPUT "port, displayed on the scanivalve controller : ", PX(1)
1940 PRINT
1950 INPUT "Enter the clearance size (t/c) : ", CLRW
1960 PRINT
1970 INPUT "Enter the contraction factor : ", CONTRC
1980 PRINT
1990 PRINT "Enter the waiting period between stepping the Scanivalve "
2000 INPUT "and beginning to collect data (in seconds) : ", WSEC
2010 PRINT
2020 INPUT "Enter the sampling period (sec) : ", AVSEC
2030 PRINT
2040 INPUT "Enter the test date : ", TDATE$
2050 PRINT
2060 INPUT "Enter the total temperature (in F) : ", TOTTMP
2070 PRINT
2080 INPUT "Enter the atmospheric pressure (mm Hg ) : ", ATNPRS
2090 PRINT
2100 PRINT "Enter the calibration coefficient for the transducer"
2110 INPUT "used for contraction pressure difference measurement (Pa/mv) : ", CALBI

```

[illegible]

[illegible]

```

3200     AVER2(IK) = ASUM2/(IK)
3210     CP(IK) = CPSUM/(IK)
3220
3230     WRITING THE RESULTS ON THE SCREEN
3240
3250     LOCATE 5,3 : PRINT IK
3260     LOCATE 5,20 : PRINT USING "###.#####"; AVER1(IK)
3270     LOCATE 12,3 : PRINT IK
3280     LOCATE 12,20 : PRINT USING "###.#####"; AVER2(IK)
3290
3300     COUNTER IS USED TO DETERMINE WHEN TO SEND THE DATA TO DISK
3310     COUNTERK = COUNTERK+1
3320     IF (COUNTERK > 15 ) GOTO 3810
3330
3340     RESET THE DAC 3497A SYSTEM : USING IOCLEAR ( ) WILL SEND A TIMER OUTPUT
3350     PULSE AND IS USED FOR STOPPING THE SCANIVALVE
3360     CALL IOCLEAR (DAC)
3370     IF PCIB.ERR = 0 THEN GOTO 3400
3380     PRINT "ERROR IN CLEARING THE DAC SYSTEM : ";PCIB.ERR$ : STOP
3390
3400     SETTING THE DAC 3497A SYSTEM TO ITS EARLIER CONFIGURATION
3410     SQ$ = "SI SDO AF4 AL5 SO1 AC4" : L = LEN(SQ$)
3420     CALL IOOUTPUTS (DAC,SQ$,L)
3430     IF PCIB.ERR = 0 THEN GOTO 3460
3440     PRINT "ERROR IN SETTING 3497A TO ITS EARLIER CONFG. : ";PCIB.ERR$ : STOP
3450
3460     IK = IK+1 : FK(IK) = FK(IK-1) + 1
3470     IF ( FK(IK) = 38 ) THEN GOTO 4020
3480     IF ( FK(IK) = 68 ) THEN GOTO 4050
3490     IF (PORTK(IK-1) < 47 ) THEN PORTK(IK) = PORTK(IK-1)+1 ELSE GOTO 3940
3500
3510     FOR IK = 1 TO 800
3520     NEXT IK
3530
3540     PREPARE THE SCREEN FOR THE SUBSEQUENT MEASUREMENT CYCLE
3550
3560     LOCATE 12,3 : PRINT " " : LOCATE 5,3 : PRINT " " : LOCATE 22,16 : PRINT " "
3570     LOCATE 12,20 : PRINT " " : LOCATE 5,20 : PRINT " "
3580
3590     INITIALIZING TIME
3600     TIMES$ = "00:00:00"
3610     RETURNING TO THE BEGINNING
3620     GOTO 3010
3630
3640
3650     ++++++ READING THE ANALOG INPUTS ++++++
3660
3670     FOR P1K = 1 TO 10000
3680     FOR P2K = 0 TO 1
3690     CALL IOOUTPUTS (DVH,SQ2$,L2)
3700     CALL IOENTER (DVH,READING(P1K,P2K))
3710     CALL IOOUTPUTS (DAC,SQ1$,L1)
3720     IF ( ( VAL(RIGHT$(TIMES$,2)) >= TOTSEC ) AND (P2K = 1)) THEN GOTO 3750
3730     NEXT P2K

```

[illegible]

5

MICRO-D

```
4260  WRITING THE RESULTS TO THE OUTPUT FILE
4270
4280  OPEN FANE2$ FOR APPEND AS #3
4290  FOR JJX = K1X TO K2X
4300      PRINT#3, USING "##.0"; JJX;
4310      PRINT#3, " ";
4320      PRINT#3, USING "##.0"; FX(JJX);
4330      PRINT#3, USING "#####.#####"; CP(JJX)
4340  NEXT JJX
4350  CLOSE 3
4360
4370  IF ( FIN2X =1 OR FIN1X = 1) GOTO 4380 ELSE K1X = K2X + 1 GOTO 3350
4380  STOP
```

E.5

```

10  DATA ACQUISITION PROGRAM FOR ENDWALL STATIC PRESSURE MEASUREMENTS
20  WITH THE HP DATA ACQUISITION SYSTEM
30
40  Set up program for MS-DOS HP-IB I/O Library
50  For use independent of the PC instrument bus system
60
70  DEF SEG
80  CLEAR ,&HFE00
90  I=&HFE00
100
110  PCIB.DIR$ represents the directory where the library files
120  are located
130  PCIB is an environment variable which should be set from MS-DOS
140  i.e. A:> SET PCIB=A:\LIB
150
160  If there is insufficient environment space a direct assignment
170  can be made here, i.e
180  PCIB.DIR$ = "A:\LIB"
190  Using the environment variable is the preferred method
200
210  PCIB.DIR$ = ENVIRON$("PCIB")
220  I$ = PCIB.DIR$ + "\PCIBILC.BLD"
230  BLOAD I$,&HFE00
240  CALL I(PCIB.DIR$, IX, JX)
250  PCIB.SEG = IX
260  IF JX=0 THEN GOTO 330
270  PRINT "Unable to load.";
280  PRINT " (Error #";JX;")"
290  STOP
300
310  Define entry points for setup routines
320
330  DEF SEG = PCIB.SEG
340  O.S = 5
350  C.S = 10
360  I.V = 15
370  I.C = 20
380  L.P = 25
390  LD.FILE = 30
400  GET.NEN = 35
410  L.S = 40
420  PANELS = 45
430
440  Establish error variables and ON ERROR branching
450
460  DEF.ERR = 50
470  PCIB.ERR$ = STRING$(64,32)
480  PCIB.NAMES$ = STRING$(16,32)
490  CALL DEF.ERR(PCIB.ERR,PCIB.ERR$,PCIB.NAMES$,PCIB.GLBERR)
500  PCIB.BASERR = 255
510  ON ERROR GOTO 830
520

```



```

530 J=-1
540 I$=PCIB.DIR$+"\HPIB.SYN"
550 CALL O.S(I$)
560 IF PCIB.ERR<>0 THEN ERROR PCIB.BASERR
570
580 Determine entry points for HP-IB Library routines
590
600 I=0
610 CALL I.V(I,IOABORT,IOCLEAR,IOCONTROL,IOENTER)
620 IF PCIB.ERR<>0 THEN ERROR PCIB.BASERR
630 CALL I.V(I,IOENTERA,IOENTERS,IOEOI,IOEOL)
640 IF PCIB.ERR<>0 THEN ERROR PCIB.BASERR
650 CALL I.V(I,IOGETTERM,IOLLOCKOUT,IOLLOCAL,IOMATCH)
660 IF PCIB.ERR<>0 THEN ERROR PCIB.BASERR
670 CALL I.V(I,IOOUTPUT,IOOUTPUTA,IOOUTPUTS,IOPOLL)
680 IF PCIB.ERR<>0 THEN ERROR PCIB.BASERR
690 CALL I.V(I,IOPOLLC,IOPOLLO,IOREMOTE,IORSET)
700 IF PCIB.ERR<>0 THEN ERROR PCIB.BASERR
710 CALL I.V(I,IOSEND,IOPOLL,IOSTATUS,IOTIMEOUT)
720 IF PCIB.ERR<>0 THEN ERROR PCIB.BASERR
730 CALL I.V(I,IOTRIGGER,J,J,J)
740 IF PCIB.ERR<>0 THEN ERROR PCIB.BASERR
750 CALL C.S
760 I$=PCIB.DIR$+"\HPIB.PLD"
770 CALL L.P(I$)
780 IF PCIB.ERR<>0 THEN ERROR PCIB.BASERR
790 GOTO 960
800
810 Error handling routine
820
830 IF ERR=PCIB.BASERR THEN GOTO 860
840 PRINT "BASIC error ";ERR;" occurred in line ";ERL
850 STOP
860 TMPERR = PCIB.ERR
870 IF TMPERR = 0 THEN TMPERR = PCIB.GLBERR
880 PRINT "PC Instrument error ";TMPERR;" detected at line ";ERL
890 PRINT "Error: ";PCIB.ERR$
900 STOP
910
920 COMMON declarations are needed if your program is going to chain
930 to other programs. When chaining, be sure to call DEF.ERR as
940 well upon entering the chained-to program
950
960 COMMON PCIB.DIR$,PCIB.SEG
970 COMMON LD.FILE,GET.NEM,PANELS,DEF.ERR
980 COMMON PCIB.BASERR,PCIB.ERR,PCIB.ERR$,PCIB.NAMES,PCIB.GLBERR
990 COMMON IOABORT,IOCLEAR,IOCONTROL,IOENTER,IOENTERA,IOENTERS,
IOEOI,IOEOL,IOGETTERM,IOLLOCKOUT,IOLLOCAL,IOMATCH,IOOUTPUT,
IOOUTPUTA,IOOUTPUTS,IOPOLL,IOPOLLC,IOPOLLO,IOREMOTE,IORSET,
IOSEND,IOPOLL,IOSTATUS,IOTIMEOUT,IOTRIGGER
1000
1010 FALSE = 0
1020 TRUE = NOT FALSE
1030 NOERR = 0

```

[illegible]

```

1580 CALL IOOUTPUTS (DAC,SQ$,L)
1590 IF PCIB.ERR = 0 THEN GOTO 1610
1600 PRINT "ERROR IN 3497A SELF TEST : ";PCIB.ERR$ : STOP
1610 INPUT "PRESS RETURN TO COMPLETE DVM SELF TEST PROCEDURE : ";DUMMY
1620 SQ$ = "ST0" : L = LEN(SQ$)
1630 CALL IOOUTPUTS (DAC,SQ$,L)
1640 IF PCIB.ERR = 0 THEN GOTO 1660
1650 PRINT "ERROR IN 3497A SELF TEST : ";PCIB.ERR$ : STOP
1660 ***
1670 PRINT
1680 PRINT "FLOW RATE MUST BE CONNECTED TO ANALOG CHANNEL 4;"
1690 PRINT "Pa-Ps(inlet) MUST BE CONNECTED TO ANALOG CHANNEL 5"
1700 INPUT "PRESS RETURN TO CONTINUE ... "; DUMMY : CLS
1710 INPUT "Do you want to continue to an existing data file (Y/N) ? ", ANW$
1720 PRINT
1730 PRINT "Enter the zero reading of the transducer used for "
1740 INPUT "contraction pressure difference (in volts): ", IN1
1750 PRINT
1760 PRINT "Enter the zero reading of the transducer used for the "
1770 INPUT "endwall data (in volts): ", IN2
1780 PRINT
1790 INPUT "Enter the output file name for raw data : ", FANE$
1800 PRINT
1810 INPUT "Enter the output file name for cp distrib. : ", FANE2$
1820 PRINT
1830 PRINT "Enter the initial column number on the endwall (1 ... 17) "
1840 INPUT " ( column number (I) increases from left to right ) : ", INIX
1850 CLS
1860 PRINT
1870 INPUT "Enter the initial row number (increases from top to button) : ", INJX
1880 PRINT
1890 INPUT "Enter the initial scanivalve port number : ", PORTX(INIX,INJX)
1900 PRINT
1910 INPUT "Enter the clearance size (t/c) : ", CLRN
1920 PRINT
1930 INPUT "Enter the contraction factor : ", CONTRC
1940 PRINT
1950 PRINT "Enter the waiting period between stepping the scanivalve "
1960 INPUT "and beginning to collect data (in seconds) : ", WSEC
1970 PRINT
1980 INPUT "Enter the sampling period (in seconds) : ", AVSEC
1990 PRINT
2000 INPUT "Enter the test date : ", TDATE$
2010 PRINT
2020 INPUT "Enter the total temperature (in F) : ", TOTTHP
2030 PRINT
2040 INPUT "Enter the atmospheric pressure ( in mmHg ) : ", ATMPRS
2050 PRINT
2060 PRINT "Enter the calibration coefficient of the transducer"
2070 INPUT "used for contraction pressure difference measurement (Pa/mv) : ", CALB1
2080 PRINT
2090 PRINT "Enter the calibration coefficient of the transducer"
2100 INPUT "used for the endwall pressure measurement (Pa/mv) : ", CALB2
2110 CLS

```

```

2120
2130     K1X = INIX :   K2X = INJX
2140     IX = INIX :   JX = INJX
2150
2160     READ THE NUMBER OF TAPS ON EACH COLUMN
2170
2180     FOR KX = 1 TO 17
2190     READ FX(KX)
2200     NEXT KX
2210     DATA 11 ,11 ,13 ,13 ,14 ,14 ,13 ,14 ,14 ,14 ,14 ,13 ,13 ,13 ,13 ,13 ,13
2220
2230
2240     WRITING THE INITIAL INFORMATION TO OUTPUT FILES
2250
2260     IF (ANW$ = "Y") OR ( ANW$ = "y" ) THEN GOTO 2670
2270     OPEN FANES$ FOR APPEND AS #2
2280     PRINT#2, " TEST DATE : "; TDATE$
2290     PRINT#2, "
2300     PRINT#2, " TIP CLEARANCE (t/c) : "; CLRN
2310     PRINT#2, "
2320     PRINT#2, " WAITING PERIOD BEFORE TAKING DATA (SEC) : "; USING "##.0"; WSEC
2330     PRINT#2, "
2340     PRINT#2, " SAMPLING PERIOD (SEC) : "; USING "##.0"; AVSEC
2350     PRINT#2, "
2360     PRINT#2, " TRANSDUCER CALIBRATION COEFFICIENTS : "
2370     PRINT#2, " FOR Psc1-Psc2 : "; USING "###.####"; CALB1
2380     PRINT#2, " FOR Ps(endwall) - Ps (inlet) : "; USING "###.####"; CALB2
2390     PRINT#2, "
2400     PRINT#2, " INITIAL TRANSDUCER READINGS (V) AT THE BEGINNING OF EXP. "
2410     PRINT#2, " Psc1 - Psc2 : "; USING "+###.#####"; IN1
2420     PRINT#2, " Ps(endwall) - Ps (inlet) : "; USING "+###.#####"; IN2
2430     PRINT#2, "
2440     PRINT#2, " CONTRACTION FACTOR : "; USING "###.####"; CONTEC
2450     PRINT#2, "
2460     PRINT#2, " TOTAL TEMPERATURE AT THE BEGINNING OF THE EXPERIMENT (IN F ) : "; TOTTMP
2470     PRINT#2, "
2480     PRINT#2, " ATMOSPHERIC PRESSURE AT THE BEGINNING OF EXP. (mm Hg) : "; ATHPRS
2490     PRINT#2, "
2500     PRINT#2, "      #   PORT #   CLM #   ROW #   Psc1 - Psc2 (V)   P-Ps (V)
2510     PRINT#2, " -----
2520     PRINT#2, "
2530     CLOSE 2
2540     OPEN FANES$ FOR APPEND AS #3
2550     PRINT#3, " TEST DATE : "; TDATE$
2560     PRINT#3, "
2570     PRINT#3, " TIP CLEARANCE (t/c) : "; CLRN
2580     PRINT#3, "
2590     PRINT#3, " WAITING PERIOD BEFORE TAKING DATA (SEC) : "; USING "##.0"; WSEC
2600     PRINT#3, "
2610     PRINT#3, " SAMPLING PERIOD (SEC) : "; USING "##.0"; AVSEC
2620     PRINT#3, "
2630     PRINT#3, "      #           CLM #           ROW #           Cp
2640     PRINT#3, " -----
2650     PRINT#3, "

```

[illegible]

```

3200     CPSUM = CPSUM + ((PS(ZX)-IN2)*CALB2)/(((Q(ZX)+Q(ZX+1))/2!)-IN1)*CALB1*CONTRC)
3210     ASUM1 = ASUM1 + Q(ZX)
3220     ASUM2 = ASUM2 + PS(ZX)
3230     NEXT ZX
3240
3250     AVERAGING THE DATA TAKEN DURING THE SAMPLING PERIOD
3260
3270     AVER1(IX,JX) = ASUM1/(IIX)
3280     AVER2(IX,JX) = ASUM2/(IIX)
3290     CP(IX,JX) = CPSUM/(IIX)
3300
3310     PRINTING THE RESULTS ON THE SCREEN
3320
3330     LOCATE 5,3 : PRINT IIX
3340     LOCATE 5,20 : PRINT USING "###.#####"; AVER1(IX,JX)
3350     LOCATE 12,3 : PRINT IIX
3360     LOCATE 12,20 : PRINT USING "###.#####"; AVER2(IX,JX)
3370
3380     KIX = IX : KJX = JX
3390
3400     COUNTERX = COUNTERX+1 : IF (COUNTERX > 15 ) THEN GOTO 3920
3410
3420     RESET THE DAC SYSTEM : USING IOCLEAR( ) COMMAND WILL SEND A TTL
3430     PULSE TO TIMER OUTPUT PORT THUS WILL STEP THE SCANVALVE
3440
3450     CALL IOCLEAR (DAC)
3460     IF PCIB.ERR = 0 THEN GOTO 3510
3470     PRINT "ERROR IN CLEARING THE DAC SYSTEM : ";PCIB.ERR$ : STOP
3480
3490     SETTING THE DAC SYSTEM TO ITS EARLIER CONFIGURATION
3500
3510     SQ$ = "SI SD0 AF4 AL5 S01 AC4" : L = LEN(SQ$)
3520     CALL IOOUTPUTS (DAC,SQ$,L)
3530     IF PCIB.ERR = 0 THEN GOTO 3550
3540     PRINT "ERROR IN SETTING 3497A TO ITS EARLIER CONFG. ";PCIB.ERR$ : STOP
3550     PTENPX = PORTX(IX,JX)
3560     JX = JX+1
3570     IF ( JX > PX(IX) ) THEN IX = IX + 1 : JX = 1
3580     IF ( IX > 17 ) THEN GOTO 3920
3590     IF(PTENPX < 47 ) THEN PORTX(IX,JX) = PTENPX + 1 ELSE GOTO 4390
3600     FOR IX = 1 TO 900
3610     NEXT IX
3620
3630     PREPARING THE SCREEN FOR THE NEXT MEASUREMENT CYCLE
3640
3650     LOCATE 12,3 : PRINT " " : LOCATE 5,3 : PRINT " " : LOCATE 22,16 : PRINT " "
3660     LOCATE 12,20 : PRINT " " : LOCATE 5,20 : PRINT " "
3670
3680     CNTX = CNTX + 1
3690     IF ( CNTX = 10 ) THEN GOSUB 4290
3700     INITIALIZING TIME TO 0.0
3710     TIMES = "00:00:00"
3720     RETURNING TO THE BEGINNING
3730     GOTO 3050

```


E.6

```

10 DATA ACQUISITION PROGRAM FOR THREE-HOLE PROB MEASUREMENTS
20 WITH THE HP DATA ACQUISITION SYSTEM
30
40 Set up program for MS-DOS HP-IB I/O Library
50 For use independent of the PC instrument bus system
60
70 DEF SEG
80 CLEAR ,&HFE00
90 I=&HFE00
100
110 PCIB.DIR$ represents the directory where the library files
120 are located
130 PCIB is an environment variable which should be set from MS-DOS
140 i.e. A:> SET PCIB=A:\LIB
150
160 If there is insufficient environment space a direct assignment
170 can be made here, i.e
180 PCIB.DIR$ = "A:\LIB"
190 Using the environment variable is the preferred method
200
210 PCIB.DIR$ = ENVIRON$("PCIB")
220 I$ = PCIB.DIR$ + "\PCIBILC.BLD"
230 BLOAD I$,&HFE00
240 CALL I(PCIB.DIR$, I$, J$)
250 PCIB.SEG = I$
260 IF J$=0 THEN GOTO 330
270 PRINT "Unable to load.";
280 PRINT " (Error $";J$;")"
290 STOP
300
310 Define entry points for setup routines
320
330 DEF SEG = PCIB.SEG
340 O.S = 5
350 C.S = 10
360 I.V = 15
370 I.C = 20
380 L.P = 25
390 LD.FILE = 30
400 GET.NEH = 35
410 L.S = 40
420 PANELS = 45
430
440 Establish error variables and ON ERROR branching
450
460 DEF.ERR = 50
470 PCIB.ERR$ = STRING$(64,32)
480 PCIB.NAMES$ = STRING$(16,32)
490 CALL DEF.ERR(PCIB.ERR,PCIB.ERR$,PCIB.NAMES$,PCIB.GLBERR)
500 PCIB.BASERR = 255
510 ON ERROR GOTO 830
520

```

```

530 J=-1
540 I$=PCIB.DIR$+"\\NPIB.SYN"
550 CALL O.S(I$)
560 IF PCIB.ERR<>0 THEN ERROR PCIB.BASERR
570
580 Determine entry points for NP-IB Library routines
590
600 I=0
610 CALL I.V(I,IOABORT,IOCLEAR,IOCONTROL,IOENTER)
620 IF PCIB.ERR<>0 THEN ERROR PCIB.BASERR
630 CALL I.V(I,IOENTERA,IOENTERS,IOKOI,IOKOL)
640 IF PCIB.ERR<>0 THEN ERROR PCIB.BASERR
650 CALL I.V(I,IOGETTERR,IOLOCKOUT,IOLOCAL,IOMATCH)
660 IF PCIB.ERR<>0 THEN ERROR PCIB.BASERR
670 CALL I.V(I,IOOUTPUT,IOOUTPUTA,IOOUTPUTS,IOPOLL)
680 IF PCIB.ERR<>0 THEN ERROR PCIB.BASERR
690 CALL I.V(I,IOPOLLC,IOPOLLS,IOREMOTE,IORSET)
700 IF PCIB.ERR<>0 THEN ERROR PCIB.BASERR
710 CALL I.V(I,IOSEND,IOSPELL,IOSTATUS,IOTIMEOUT)
720 IF PCIB.ERR<>0 THEN ERROR PCIB.BASERR
730 CALL I.V(I,IOTRIGGER,J,J,J)
740 IF PCIB.ERR<>0 THEN ERROR PCIB.BASERR
750 CALL C.S
760 I$=PCIB.DIR$+"\\NPIB.PLD"
770 CALL L.P(I$)
780 IF PCIB.ERR<>0 THEN ERROR PCIB.BASERR
790 GOTO 960
800
810 Error handling routine
820
830 IF ERR=PCIB.BASERR THEN GOTO 860
840 PRINT "BASIC error ";ERR;" occurred in line ";LNL
850 STOP
860 TNPERR = PCIB.ERR
870 IF TNPERR = 0 THEN TNPERR = PCIB.GLBERR
880 PRINT "PC Instrument error ";TNPERR;" detected at line ";LNL
890 PRINT "Error: ";PCIB.ERR$
900 STOP
910
920 COMMON declarations are needed if your program is going to chain
930 to other programs. When chaining, be sure to call DEF.ERR as
940 well upon entering the chained-to program
950
960 COMMON PCIB.DIR$,PCIB.SEG
970 COMMON LD.FILE,GET.NEM,PANELS,DEF.ERR
980 COMMON PCIB.BASERR,PCIB.ERR,PCIB.ERR$,PCIB.NAMES,PCIB.GLBERR
990 COMMON IOABORT,IOCLEAR,IOCONTROL,IOENTER,IOENTERA,IOENTERS,IOKOI,
IOKOL,IOGETTERR,IOLOCKOUT,IOLOCAL,IOMATCH,IOOUTPUT,
IOOUTPUTA,IOOUTPUTS,IOPOLL,IOPOLLC,IOPOLLS,IOREMOTE,IORSET,
IOSEND,IOSPELL,IOSTATUS,IOTIMEOUT,IOTRIGGER
1000
1010 FALSE = 0
1020 TRUE = NOT FALSE
1030 NOERR = 0

```


[illegible]

```

2120 PRINT " P3 MUST BE CONNECTED TO ANALOG CHANNEL # 7"
2130 PRINT
2140
2150 INPUT " Enter the purpose of the experiment : ", ANSW$
2160 IX = 1
2170 CLS
2180 CHKX = 1
2190 PRINT "
2200 PRINT " Enter the zero value of transducer used for contraction "
2210 INPUT " pressure difference measurement (Setra 52936) : ", INQ(IX)
2220 PRINT
2230 PRINT " Enter the zero value of transducer used for P1 "
2240 INPUT " measurement ( Rosemount 633 ) : ", IN1(IX)
2250 PRINT
2260 PRINT " Enter the zero value of transducer used for P2 "
2270 INPUT " measurement ( Rosemount 591 ) : ", IN2(IX)
2280 PRINT
2290 PRINT " Enter the zero value of transducer used for P3 "
2300 INPUT " measurement ( Rosemount 567 ) : ", IN3(IX)
2310 PRINT
2320 INPUT " Enter the total temperature (F) : ", TOTTMP(IX)
2330 PRINT
2340 INPUT " Enter the atmospheric pressure (mmHg) : ", ATMPRS(IX)
2350 CLS
2360 PREPARE THE SCREEN FOR DATA ACQUISITION
2370
2380 LOCATE 22,35 : PRINT ANSW$
2390 LOCATE 15,40 : PRINT " WAITING PERIOD (SEC) : "; WSEC
2400 LOCATE 17,40 : PRINT " SAMPLING PERIOD (SEC) : "; AVSEC
2410 LOCATE 5,8 : PRINT "Psc1-Psc2 = "
2420 LOCATE 7,8 : PRINT "P1 - Ps = "
2430 LOCATE 9,8 : PRINT "P2 - Ps = "
2440 LOCATE 11,8 : PRINT "P3 - Ps = "
2450 LOCATE 22,8 : PRINT "SECCNDS : "
2460 LOCATE 15,8 : PRINT "STATION # "
2470
2480 <<<< PREPARING THE DAC 3497A SYSTEM FOR DATA ACQUISITION >>>>
2490
2500 SQ$ = "SI SDO AF4 AL7 S01 AC4" L = LEN(SQ$)
2510 CALL IOOUTPUTS (DAC,SQ$,L)
2520 IF PCIB.ERR = 0 THEN GOTO 2550
2530 PRINT "ERROR IN PREPARING THE DAC 3497A SYSTEM : PCIB.ERR$ STOP
2540
2550 <<<< PREPARING DVM 3456A SYSTEM FOR DATA ACQUISITION >>>>
2560
2570 SQ$ = "H DO PQ S0F1 R4 6STG 1STI Z0 FLO S01" L = LEN(SQ$)
2580 CALL IOOUTPUTS (DVM,SQ$,L)
2590 IF PCIB.ERR = 0 THEN GOTO 2620
2600 PRINT "ERROR IN PREPARING THE DVM 3456A SYSTEM : PCIB.ERR$ STOP
2610
2620 SQ1$ = "AS" L1 = LEN(SQ1$)
2630 SQ2$ = "T3" L2 = LEN(SQ2$)
2640
2650 INITIALIZING THE TIME

```

```

2660
2670     TIME$ = "00:00:00"
2680
2690 LOCATE 15,17 : PRINT USING "###" ; IX
2700 IF (VAL(RIGHT$(TIME$,2)) = 0 ) THEN LOCATE 18,16 : PRINT "WAITING"
2710 IF (VAL(RIGHT$(TIME$,2)) < WSEC ) THEN GOTO 2690
2720 IF (VAL(RIGHT$(TIME$,2)) = WSEC ) THEN LOCATE 18,16 : PRINT "
2730
2740     ++++++ READING THE ANALOG INPUTS ++++++
2750
2760     FOR P1% = 1 TO 10000
2770     FOR P2% = 0 TO 3
2780         CALL IOOUTPUTS (DVM,SQ2$,L2)
2790         CALL IOENTER (DVM,READING(P1%,P2%))
2800         CALL IOOUTPUTS (DAC,SQ1$,L1)
2810         IF ( ( VAL(RIGHT$(TIME$,2)) >= TOTSEC ) AND (P2% = 3)) THEN GOTO 2840
2820     NEXT P2%
2830 NEXT P1%
2840 IIX = P1%
2850 FOR P1% = 1 TO IIX
2860     Q(P1%) = READING(P1%,0) : PS1(P1%) = READING(P1%,1)
2870     PS2(P1%) = READING(P1%,2) : PS3(P1%) = READING(P1%,3)
2880 NEXT P1%
2890
2900 LOCATE 22,16 : PRINT RIGHT$(TIME$,2)
2910 ASUMQ = 0! : ASUM1 = 0! : ASUM2 = 0! : ASUM3 = 0!
2920 FOR ZX = 1 TO IIX
2930     ASUMQ = ASUMQ + Q(ZX)
2940     ASUM1 = ASUM1 + PS1(ZX)
2950     ASUM2 = ASUM2 + PS2(ZX)
2960     ASUM3 = ASUM3 + PS3(ZX)
2970 NEXT ZX
2980
2990     AVERQ(IIX) = ASUMQ/(IIX)
3000     AVER1(IIX) = ASUM1/(IIX)
3010     AVER2(IIX) = ASUM2/(IIX)
3020     AVER3(IIX) = ASUM3/(IIX)
3030
3040     WRITING THE RESULTS ON THE SCREEN
3050
3060     LOCATE 5,3 : PRINT IIX
3070     LOCATE 5,20 : PRINT USING "###.#####", AVERQ(IIX)
3080     LOCATE 7,3 : PRINT IIX
3090     LOCATE 7,20 : PRINT USING "###.#####"; AVER1(IIX)
3100     LOCATE 9,3 : PRINT IIX
3110     LOCATE 9,20 : PRINT USING "###.#####"; AVER2(IIX)
3120     LOCATE 11,3 : PRINT IIX
3130     LOCATE 11,20 : PRINT USING "###.#####"; AVER3(IIX)
3140
3150 LOCATE 8,33 : INPUT "PRESS RETURN TO CONTINUE \ 'N' TO STOP : ".ANW$
3160 IF (IX = STX) OR (ANW$ = "N") THEN GOTO 3530
3170 LOCATE 8,33 : PRINT
3180     IX = IX+1
3190     ZCO(IX) = ZCO(IX-1) + ZSTP*.001*25.4

```

[illegible]

```

3740 PRINT#2, USING "###.8"; JJX;
3750 PRINT#2, " ";
3760 PRINT#2, USING "+###.88"; YCO;
3770 PRINT#2, " ";
3780 PRINT#2, USING "+###.88"; YCO;
3790 PRINT#2, " ";
3800 PRINT#2, USING "+###.88"; ZCO(JJX);
3810 PRINT#2, " ";
3820 PRINT#2, USING "+###.88"; ATMPRS(JJX);
3830 PRINT#2, " ";
3840 PRINT#2, USING "+###.88"; TOTTHP(JJX)
3850     NEXT JJX
3860 PRINT#2, " "
3870 PRINT#2, "  #    INP  Pac1-Pac2  INP1    P1    INP2    P2    INP3    P3 "
3880 PRINT#2, " -----"
3890 PRINT#2, " "
3900             FOR JJX = 1 TO IX
3910 PRINT#2, USING "###"; JJX;
3920 PRINT#2, " ";
3930 PRINT#2, USING "+#.###"; INQ(JJX);
3940 PRINT#2, " ";
3950 PRINT#2, USING "+#.####"; AVERQ(JJX);
3960 PRINT#2, " ";
3970 PRINT#2, USING "+#.###"; IN1(JJX);
3980 PRINT#2, " ";
3990 PRINT#2, USING "+#.####"; AVER1(JJX);
4000 PRINT#2, " ";
4010 PRINT#2, USING "+#.###"; IN2(JJX);
4020 PRINT#2, " ";
4030 PRINT#2, USING "+#.####"; AVER2(JJX);
4040 PRINT#2, " ";
4050 PRINT#2, USING "+#.###"; IN3(JJX);
4060 PRINT#2, " ";
4070 PRINT#2, USING "+#.####"; AVER3(JJX)
4080     NEXT JJX
4090     CLOSE 2
4100     OPEN FAME2$ FOR APPEND AS #3
4110 PRINT#3, TDATE$; " "; STN$
4120 PRINT#3, STX; " "; CLRN
4130     FOR JJX = 1 TO IX
4140 PRINT#3, USING "####.88"; XCO;
4150 PRINT#3, " ";
4160 PRINT#3, USING "####.88"; YCO;
4170 PRINT#3, " ";
4180 PRINT#3, USING "####.88"; ZCO(JJX);
4190 PRINT#3, " ";
4200 PRINT#3, USING "####.88"; ATMPRS(JJX);
4210 PRINT#3, " ";
4220 PRINT#3, USING "###.88"; TOTTHP(JJX);
4230 PRINT#3, " ";
4240 PRINT#3, USING "###.8"; ALPHA
4250     NEXT JJX
4260     FOR JJX = 1 TO IX
4270 PRINT#3, USING "##.#####"; IN1(JJX);

```



```
4280 PRINT#3, " ";
4290 PRINT#3, USING "##.#####"; AVER1(JJX);
4300 PRINT#3, " ";
4310 PRINT#3, USING "##.#####"; IN2(JJX);
4320 PRINT#3, " ";
4330 PRINT#3, USING "##.#####"; AVER2(JJX);
4340 PRINT#3, " ";
4350 PRINT#3, USING "##.#####"; IN3(JJX);
4360 PRINT#3, " ";
4370 PRINT#3, USING "##.#####"; AVER3(JJX);
4380 PRINT#3, " ";
4390 PRINT#3, USING "##.#####"; INQ(JJX);
4400 PRINT#3, " ";
4410 PRINT#3, USING "##.#####"; AVERQ(JJX)
4420     NEXT JJX
4430 CLOSE 3
4440
4450 CLS
4460 IF (IX = STX) THEN INPUT " DO YOU WANT TO CONTINUE (Y/N) ? ", AS$
4470 IF ( AS$ = "Y" ) OR ( AS$ = "y" ) THEN GOTO 1720
4480 STOP
```

APPENDIX F

Program Used for the Calculation of the Inlet Endwall Boundary Layer Parameters

The program uses the trapezoidal rule for the integrals of the displacement and momentum thicknesses. It has been coded in Turbo Pascal and is to be compiled on an IBM compatible micro computer.

```

program Boundary; { Calculates momentum and displacement thicknesses of
                  the boundary layer, and concludes the state of the layer
                  by making use of the shape factor

```

```

    For numerical integration Trapezoidal rule is used. }

```

```

type

```

```

    datapoint = array [1..300] of real;

```

```

var

```

```

    displths : real; { Displacement thickness of the boundary layer (mm)}

```

```

    momths : real; { Momentum thickness of the boundary layer (mm)}

```

```

    m_integrand : datapoint; { array for 1-u/Ue values }

```

```

    d_integrand : datapoint; { array for u/Ue.(1-u/Ue) values }

```

```

    pointno : integer; { Number of datapoints;
                       excludes the point on the surface.}

```

```

    u_Ue : datapoint; { array for u/Ue values }

```

```

    z : datapoint; { array for z values }

```

```

    u_Uc1 : datapoint; { array for velocity/(center line velocity) values }

```

```

    z_span : datapoint; { array for z/span values }

```

```

    I : integer;

```

```

    H : real; { boundary layer shape factor }

```

```

    layercondt : string[25];

```

```

    infile1, infile2, outfile1, outfile2, outfile3 : text;

```

```

    infil1, infil2, outfil1, outfil2, outfil3 : string[25];

```

```

begin { beginning of the main program }

```

```

    Clrscr;

```

```

    Writeln ( ' ');

```

```

    Writeln ( ' Number of the points should not include the point on the surface ');

```

```

    Writeln ( ' ');

```

```

    Write ( ' Enter number of points : '); Readln (pointno);

```

```

    Writeln ( ' ');

```

```

    Write ( ' Enter name of the input file name for z values : ');

```

```

    Readln (infil1);

```

```

    Writeln ( ' ');

```

```

    Write ( ' Enter name of the input file name for v values : ');

```

```

    Readln (infil2);

```

```

    Writeln ( ' ');

```

```

      rscr;

      outfil1 := 'bdry.out';
      outfil2 := 'bdryx.out';
      outfil3 := 'bdryv.out';

      { Read the input data }

      Assign (infile1, infil1);
      Reset (infile1);
      for I := 2 to pointno+1 do
        Readln (infile1, z_span[I]);
      Close (infile1);

      Assign (infile2, infil2);
      Reset (infile2);
      for I := 2 to pointno+1 do
        Readln (infile2, u_Ucl[I]);
      Close (infile2);

      { Calculating z (mm) and u/Ue }

      for I := 2 to pointno+1 do begin

        u_Ue[I] := u_Ucl[I] / u_Ucl[pointno+1];
        z[I] := z_span[I]*210.0;

      end;
      { calculating the integrands for momentum and displacement
        thicknesses :}

      for I := 2 to pointno+1 do begin

        d_integrand[I] := 1.0 - u_Ue[I];
        m_integrand[I] := u_Ue[I]*( 1.0 - u_Ue[I]) ;

      end;

      d_integrand[1] := 1.0;
      m_integrand[1] := 0.0;
      z[1] := 0.0;
      u_Ue[1] := 0.0;

      dispths := 0.0;
      momths := 0.0;

      { calculating the displacement and momentum thicknesses
        using trapezoidal rule :}

      For I := 1 to pointno do begin
        dispths := dispths + (d_integrand[I] + d_integrand[I+1])*(z[I+1]-z[I])/2.0;
        momths := momths + (m_integrand[I] + m_integrand[I+1])*(z[I+1]-z[I])/2.0;
      end;

```

```

    { Calculating the shape factor }

    H := dispths/months;

    If ( H > 2.1 ) then

        layercondt := 'laminar'

    else

        layercondt := 'turbulent' ;

    { Writing the results to output files : }

Assign (outfile1,outfil1);
Rewrite (outfile1);
Writeln (outfile1, ' ');
Writeln (outfile1, 'Boundary layer at the cascade inlet is', layercondt);
Writeln (outfile1, ' ');
Writeln (outfile1, 'Boundary layer shape factor ', H:6:3);
Writeln (outfile1, ' ');
Writeln (outfile1, 'Displacement thickness (mm) : ', dispths:7:4);
Writeln (outfile1, ' ');
Writeln (outfile1, 'Momentum thickness (mm) : ', months:7:4);
Writeln (outfile1, ' ');
Writeln (outfile1, '      y/theta      u/Ue      ');
Writeln (outfile1, '-----');
Writeln (outfile1, ' ');
    for I := 1 to pointno+1 do
        Writeln ( outfile1,I:3, ' ', z[I]/months:8:5, ' ', u_Ue[I]:9:7);
Close (outfile1);

Assign (outfile2,outfil2);
Rewrite (outfile2);
    for I := 1 to pointno+1 do
        Writeln ( outfile2,z[I]/months:8:5);
Close (outfile2);

Assign (outfile3,outfil3);
Rewrite (outfile3);
    for I := 1 to pointno+1 do
        Writeln ( outfile3,u_Ue[I]:8:5);
Close (outfile3);

end.

```

APPENDIX G

Tip Clearance Actual Mass Flow Rate Calculation Program

The input to the program is the processed three-hole probe data. One of the output files of the data reduction program listed in Appendix C is suitable for input to this program. For integration, each panel formed by four measurement points (Fig. G.1) is considered separately: the velocity component normal to the panel is determined at each corner of the panel (note that for the panels adjacent to the blade tip or to the endwall, no slip boundary condition is used). The panel is divided into two triangles and, owing to the fact that the measurement points were closely spaced, the variation of the mass flow rate within each of the triangles is assumed to be a first order function of x and s (see Fig. G.1). Then the mass flow rate through each triangle is determined by numerical integration using the Gaussian Quadrature method. Output of the program is the tip gap total mass flow rate (nondimensionalized as discussed in section 7.1) and the chordwise distribution of the tip gap mass flow rate. In a separate file the nondimensional mass flow rate at each measurement station is also output which will then be used for determining the chordwise mass averaged total pressure loss distribution.

The program has been coded in Turbo Pascal and is to be compiled on an IBM compatible micro computer.

Fig. G.1 Panel Used For Tip Clearance Mass Flow Rate Calculation


```
program massflow;
```

```
{ TIP GAP MASS FLOW RATE CALCULATION, BASED ON THREE-HOLE PROBE MEASUREMENTS  
  WITHIN THE TIP CLEARANCE }
```

```
type
```

```
  Datapoint    = array [1..37,1..16] of real;
```

```
  Panelarray   = array [1..37,1..16,1..4] of real;
```

```
  Solvec       = array [1..4] of real;
```

```
  Solvec2      = array [1..3] of real;
```

```
var
```

```
  Mass_stn     : array [1..37] of real;
```

```
  Q            : real; { Dynamic pressure at the data point (input) }
```

```
  VVin        : datapoint; { V (data point) / V (inlet centerline) }
```

```
  Xdat        : Datapoint; { x co-ordinate of the data point (mm) (input) }
```

```
  Ydat        : Datapoint; { y co-ordinate of the data point (mm) (input) }
```

```
                { x axis is tangent to blade pressure side }
```

```
  Zdat        : Datapoint; { z co-ordinate of the data point (input) }  
                { stepsize in z direction is assumed to be 0.508 mm;  
                if this is not the case modify the program }
```

```
{ each panel is addressed by its first corner;  
  see sketch for numbering }
```

```
  Panelxy     : Datapoint; { length of the xy edge of each panel  
                           also will be used as the upper limit for  
                           triangle 234 during integration for  
                           variable x }
```

```
  Panelz      : real; { length of spanwise edge of each panel }
```

```
  Panelalpha  : real; { angle of the panel relative to the horizontal  
                      test rig axis }
```

```
  Qnorm       : real;
```

```
  Tinlet, Psinlet : real; { inlet static temperature and pressure (input) }
```

```
  Area        : real; { area of each panel }
```

```
  Areasum     : real; { Sum of panel areas }
```

```
  Areasum2    : real; { Sum of panel areas at a particular chordwise }
```

```

station )

Beta      : Datapoint; { flow angle relative to the horizontal test rig
                        axis at the data point. Positive when
                        flow is towards the bottom of the test rig
                        ( Note that this is the opposite of the
                        sign convention used in the outputs of
                        the three-hole probe data reduction program )

PanBeta   : Panelarray; { angle between the flow direction and the
                        normal vector of the panel; third dimension
                        indicates the corner number of the panel where
                        this angle is defined [1..4] }

Density   : Datapoint; { input },

Vpanel    : Panelarray; { it differs from V by the third dimension
                        which indicates the corner number of the
                        panel }

Mpanel    : Datapoint; { mass flow rate through each panel }

Mtip      : real; { total mass flow rate through the gap
                  ( nondimensionalized by passage inlet mass flow rate ) }

I, J, M    : integer; { I addresses the data point along the center line
                        J addresses the data point across the gap;
                        M is the maximum number of measurements taken
                        at a chordwise station }

JJ, ZZ     : Integer;

Bad        : Datapoint; { Data points for which experimental error is
                        present }

tipclr     : real; { tip clearance (t/c) }

Re         : real; { Reynolds number based on cascade inlet velocity
                  and blade chord }

vector1, vector2, vectorn : Smlvec2;

ACF : Smlvec;

X1, X21, X22, Z1, Z2, V1, Integ123, Integ234 : real;

infile1, outfile1, outfile2, outfile3 : text;

infil1, outfil1, outfil2, outfil3, AWR : string[25];

( The following temporary parameters are used at different parts of the
  mass flow rate calculation )

```

[illegible]

```

Writeln ( ' ');
Write ( ' Enter the Reynolds number ( based on Vinlet and chord ) : ');
Readln (Re);

Writeln ( ' ');
Write ( ' Enter input file name : '); Readln (infile1);

Writeln ( ' ');
Write ( ' Enter output file name for table outputs : ');
Readln (outfill1);

Writeln ( ' ');
Write ( ' Enter output file name for total mass flow rate at each stn : ');
Readln (outfil2);

Writeln ( ' ');
Write ( ' Enter output file name for mass flow rate at each datapoint : ');
Writeln ( ' (will be used for mass averaged total pressure) ');
Write ( ' loss coefficient calculation : ');
Readln (outfil3);

Writeln ( ' ');
Writeln ( ' Press any key to continue ... ');
Repeat until KeyPressed; Clrscr;
Writeln ( ' ');
Writeln ( ' Enter the maximum number of measurement stations across the gap ');
Write ( ' for this particular data set : '); Readln (M);
Writeln ( ' ');
Writeln ( ' If M>14 then the array sizes in the program must be increased ');

M := M + 2; { including the blade tip and endwall surface points for which
              V = 0.0 }
Writeln ( ' ');
Write ( ' Are the Z data point co-ordinates in mm ? (Y/N) '); Readln (AWR);
Writeln ( ' ');
Writeln ( ' Press any key to continue ... ');
Repeat until KeyPressed;
Clrscr;

{ Initializing the arrays }

For I := 1 to M do begin
    Mass_stn[I] := 0.0;
    For J := 1 to M do begin
        Bad[I,J] := 0.0;
    end;
end;

{ Read input data }

Assign (infile1,infill1);
Reset (infile1);

for I := 1 to M do begin

```

```

Readln ( infile1,ZZ);
for J := 2 to ZZ+1 do begin
  Readln ( infile1,Xdat[I,J], Ydat[I,J], Zdat[I,J], VVin[I,J],
           Density[I,J], Q, Tinlet, Psinlet, Beta[I,J]);
  If (( Q <= 0.0) or (Abs(Beta[I,J]) > 80.0)) then Bad[I,J] := 5.0;
  Density[I,J] := Density[I,J]/(Psinlet/(287.0*Tinlet));
end;
If ( ZZ < N-2 ) then begin
  For J := ZZ+2 to N-1 do begin
    Xdat[I,J] := Xdat[I,J-1]; Ydat[I,J] := Ydat[I,J-1];
    If ( (AWR = 'n') or (AWR = 'N') ) then
      Zdat[I,J] := Zdat[I,J-1] + 20.0 else
      Zdat[I,J] := Zdat[I,J-1] + 0.508;

    VVin[I,J] := VVin[I,J-1];
    Density[I,J] := Density[I,J-1]; Beta[I,J] := Beta[I,J-1];
    Bad[I,J] := Bad[I,J-1];
  end;
end;
end;
Close (infile1);

{ Defining the co-ordinates of the points on the blade tip and on the endwall.
  Also defining the dynamic pressure and flow angle at these points. }

For I := 1 to N do begin
  Xdat[I,1] := Xdat[I,2];
  Ydat[I,1] := Ydat[I,2];
  Zdat[I,1] := 0.0;
  VVin[I,1] := 0.0;
  Beta[I,1] := 0.0;
  Xdat[I,N] := Xdat[I,2];
  Ydat[I,N] := Ydat[I,2];
  Zdat[I,N] := tipclr*250;
  VVin[I,N] := 0.0;
  Beta[I,N] := 0.0;
  Density[I,N] := Density[I,N-1];
  Density[I,1] := Density[I,2];
end;

{ If necessary, converting the z scale to mm and adding half probe thickness
  to all z values }

If ( ( AWR = 'N' ) or ( AWR = 'n' ) ) then begin
  For I := 1 to N do begin
    For J := 2 to N-1 do
      Zdat[I,J] := Zdat[I,J]*0.001*25.4 + hprobe;
    end;
  end
else begin
  For I := 1 to N do begin
    For J := 2 to N-1 do

```

```

      Zdat[I,J] := Zdat[I,J] + hprobe,
    end;
  end;
end;

```

```
{ Calculating the panel xy edge length in millimeters ( since there are N*M
data points, number of panels will be (N-1)*(M-1) ) }
```

```

For I := 1 to M-1 do begin
  For J := 1 to M-1 do
    Panelxy[I,J] := sqrt(sqr(Xdat[I+1,J]-Xdat[I,J])
                        + sqr(Ydat[I+1,J]-Ydat[I,J]));

```

```
( Converting the flow angle (beta) from degrees to radian and changing the
  sign ( positive flow angle for downwards flow ) )
```

```

For I := 1 to N do begin
  For J := 1 to M do
    Beta[I,J] := -Beta[I,J]*Pi/180.0
end;

```

{ The flow angle and velocities with experimental error will be replaced by the values obtained from interpolation }

```

For I := 2 to N-1 do begin
  For J := 2 to N-1 do begin
    If A[I,J] = 0 then
      A[I,J] := A[I-1,J-1] + A[I-1,J] + A[I,J-1]
  end
end

```

```
Zextend := true;
Xextend := true;
```

```

If ( Bad[I,J] = 5.0) then begin
  Writeln ( ' Point ',I:3, ', ',J:3, ' has exp. error' );
  V_1 := VVin[I-1,J]; V_2 := VVin[I+1,J];
  V_3 := VVin[I,J+1]; V_4 := VVin[I,J-1];
  B_1 := Beta[I-1,J]; B_2 := Beta[I+1,J];
  B_3 := Beta[I,J+1]; B_4 := Beta[I,J-1];
  Z_1 := Zdat[I-1,J]; Z_2 := Zdat[I+1,J];
  Z_3 := Zdat[I,J+1]; Z_4 := Zdat[I,J-1];
  X_1 := Xdat[I-1,J]; X_2 := Xdat[I+1,J];
  X_3 := Xdat[I,J+1]; X_4 := Xdat[I,J-1];
  Y_1 := Ydat[I-1,J]; Y_2 := Ydat[I+1,J];
  Y_3 := Ydat[I,J+1]; Y_4 := Ydat[I,J-1];

```

```

If (Bad[I-1,J] = 5.0) then begin
  Writeln ( ' Point ',I-1:3, ' ',J:3, ' has also exp. error' );
  Writeln ( ' Therefore if possible point ',I-2:3, ' ',J:3, ' will be ' );
  Writeln ( ' used for the interpolation of point ',I:3, ' ',J:3);
  If (I >= 3) and ( Bad[I-2,J] <> 5.0 ) then begin
    Z_1 := Zdat[I-2,J]; X_1 := Xdat[I-2,J];
    Y_1 := Ydat[I-2,J]; V_1 := VVin[I-2,J]; B_1 := Beta[I-2,J];
  end
else begin

```

```

        Writeln ( ' ');
        Writeln ( ' But, it is not possible; interpolation will be done');
        Writeln ( ' only in z direction. ');
        Zextend := false;
    end;
end;

If (Bad[I+1,J] = 5.0) then begin
    Writeln ( ' Point ',I+1:3,' ',J:3,' has also exp. error');
    Writeln ( ' Therefore if possible point ',I+2:3,' ',J:3,' will be ');
    Writeln ( ' used for the interpolation of point ',I:3,' ',J:3);
    Writeln ( ' ');
    If (I <= N-2) and (Bad[I+2,J] <> 5.0) then begin
        Z_2 := Zdat[I+2,J]; X_2 := Xdat[I+2,J];
        Y_2 := Ydat[I+2,J]; V_2 := VWin[I+2,J]; B_2 := Beta[I+2,J];
    end
    else begin
        Writeln ( ' ');
        Writeln ( ' But, it is not possible; interpolation will be done');
        Writeln ( ' only in z direction. ');
        Zextend := false;
    end;
end;

If (Bad[I,J+1] = 5.0) then begin
    Writeln ( ' Point ',I:3,' ',J+1:3,' has also exp. error');
    Writeln ( ' Therefore if possible point ',I:3,' ',J+2:3,' will be ');
    Writeln ( ' used for the interpolation of point ',I:3,' ',J:3);
    Writeln ( ' ');
    If (J <= 14) and (Bad[I,J+2] <> 5.0) then begin
        Z_3 := Zdat[I,J+2]; X_3 := Xdat[I,J+2];
        Y_3 := Ydat[I,J+2]; V_3 := VWin[I,J+2]; B_3 := Beta[I,J+2];
    end
    else begin
        Writeln ( ' ');
        Writeln ( ' But, it is not possible; interpolation will be done');
        Writeln ( ' only in x direction. ');
        Zextend := false;
    end;
end;

If (Bad[I,J-1] = 5.0) then begin
    Writeln ( ' Point ',I:3,' ',J-1:3,' has also exp. error');
    Writeln ( ' Therefore if possible point ',I:3,' ',J-2:3,' will be ');
    Writeln ( ' used for the interpolation of point ',I:3,' ',J:3);
    Writeln ( ' ');
    If (J >= 3) and (Bad[I,J-2] <> 5.0) then begin
        Z_4 := Zdat[I,J-2]; X_4 := Xdat[I,J-2];
        Y_4 := Ydat[I,J-2]; V_4 := VWin[I,J-2]; B_4 := Beta[I,J-2];
    end
    else begin
        Writeln ( ' ');
        Writeln ( ' But, it is not possible; interpolation will be done');
        Writeln ( ' only in x direction. ');
    end;
end;

```

```

        Zextend := false,
    end;
end;

{ If B_4 is the blade tip or B_3 is the endwall they will not be
  used as 0.0 during the interpolation : }

    If ( B_3 = 0.0 ) then B_3 := B_4;
    If ( B_4 = 0.0 ) then B_4 := B_3;

{ Corners of panel2 : if I,J is the point with experimental error,
  the corners of the corresponding Panel2 will be I+1,J-1 ; I+1,J+1 ;
  I-1,J-1 ; I-1,J+1 . If one of these points has also exp. error, Panel2
  will be extended to the next pair of datapoints in this direction (i.e.,
  if point I-1,J-1 has error I-2,J-2 and I-1,J+1 will be used etc.) }

    Panel2alpha := -Arctan((Y_1-Y_2)/(X_1-X_2)) + (90 - 52.4)*Pi/180.0;

{ The following parameters are the flow angles relative to the normal
  vector of Panel2 at points I-1,J ; I+1,J I,J-1 and I,J+1
  ( in most cases they are the midpoints of the edges of Panel2 ) }

    Pan2Beta1 := 0.5*Pi - ( B_1 + Panel2alpha );
    Pan2Beta2 := 0.5*Pi - ( B_2 + Panel2alpha );
    Pan2Beta3 := 0.5*Pi - ( B_3 + Panel2alpha );
    Pan2Beta4 := 0.5*Pi - ( B_4 + Panel2alpha );

{ Calculating the velocity components normal and tangent to Panel2 }

    Pan2V1_N := V_1*Cos(Pan2Beta1);
    Pan2V2_N := V_2*Cos(Pan2Beta2);
    Pan2V3_N := V_3*Cos(Pan2Beta3);
    Pan2V4_N := V_4*Cos(Pan2Beta4);

    Pan2V1_T := V_1*Sin(Pan2Beta1);
    Pan2V2_T := V_2*Sin(Pan2Beta2);
    Pan2V3_T := V_3*Sin(Pan2Beta3);
    Pan2V4_T := V_4*Sin(Pan2Beta4);

{ Calculating the distances between points ; will be used in the
  interpolation procedure }

    deltax1 := Sqrt( Sqr(Xdat[I,J] - X_1) + Sqr(Ydat[I,J] - Y_1) );
    deltax2 := Sqrt( Sqr(Xdat[I,J] - X_2) + Sqr(Ydat[I,J] - Y_2) );
    deltas1 := Abs(-Zdat[I,J] + Z_3);
    deltas2 := Abs(-Z_4 + Zdat[I,J]);

{ Linear interpolation for both components of velocity : ( For each
  component interpolation will be done in x and z directions and
  the average will be taken for determining the last value of
  each component ) }

    V_XN := ( Pan2V2_N - Pan2V1_N )*deltas1/( deltax1 + deltax2 ) + Pan2V1_N;

```



```

V_ZN := ( Pan2V4_M - Pan2V3_M ) * deltax1 / ( deltax1 + deltax2 ) + Pan2V3_M;
V_XT := ( Pan2V2_T - Pan2V1_T ) * deltax1 / ( deltax1 + deltax2 ) + Pan2V1_T;
V_ZT := ( Pan2V4_T - Pan2V3_T ) * deltax1 / ( deltax1 + deltax2 ) + Pan2V3_T;

If ( Xextend = False ) then begin
V_XN := V_ZN; V_XT := V_ZT;
end;

If ( Zextend = False ) then begin
V_ZN := V_XN; V_ZT := V_XT;
end;

If ( Xextend = False ) and ( Zextend = False ) then begin
Writeln ( 'Point ', I, J, ' cannot be interpolated ' );
Writeln ( ' Press any key to continue or Ctrl Break to stop ' );
Repeat Until Keypressed;
end;

{ Calculating the average velocity components : }

V_M := ( V_ZN + V_XN ) / 2.0;
V_T := ( V_XT + V_ZT ) / 2.0;

{ Calculating the resultant velocity : }

VVin[I,J] := Sqrt ( Sqr(V_M) + Sqr(V_T) );

Writeln ( ' Resultant velocity from interpolation ', VVin[I,J] : 12:6 );

{ Calculating the flow angle at this point : }

Beta[I,J] := 0.5 * Pi - arctan ( V_T / V_M ) - Panel2alpha;

Writeln ( ' Resultant flow angle from interpolation ', Beta[I,J] : 12:6 );
Writeln ( ' Press any key to continue ... ' );

Repeat until Keypressed;

end;
end;
end;

Clrscr;

{ For stations I = 1 and I = 52 if interpolation is necessary only
z direction will be considered : }

For I := 1 to N do begin
While ( I = 1 ) or ( I = 52 ) do begin

For J := 2 to N-1 do begin

```

```

Zextend := true;
Iextend := true;

```

```

If ( Bad[I,J] = 5.0 ) then begin

```

```

  Writeln ( ' Point ',I:3,' ',J:3,' has experimental error' );
  Writeln ( ' Interpolation will be done only in the z direction ' );

```

```

  V_3 := VVin[I,J+1]; V_4 := VVin[I,J-1];
  B_3 := Beta[I,J+1]; B_4 := Beta[I,J-1];
  Z_3 := Zdat[I,J+1]; Z_4 := Zdat[I,J-1];
  X_3 := Xdat[I,J+1]; X_4 := Xdat[I,J-1];
  Y_3 := Ydat[I,J+1]; Y_4 := Ydat[I,J-1];

```

```

  If (Bad[I,J+1] = 5.0) then begin

```

```

    Writeln ( ' Point ',I:3,' ',J+1:3,' has also exp. error' );
    Writeln ( ' Therefore point ',I:3,' ',J+2:3,' will be used for ' );
    Writeln ( ' the interpolation of point ',I:3,' ',J:3);
    Writeln ( ' ');

```

```

    If (J <= 14) and ( Bad[I,J+2] <> 5.0 ) then begin

```

```

      Z_3 := Zdat[I,J+2]; X_3 := Xdat[I,J+2];
      Y_3 := Ydat[I,J+2]; V_3 := VVin[I,J+2]; B_3 := Beta[I,J+2];

```

```

    end

```

```

  else begin

```

```

    Writeln ( ' ');
    Writeln ( ' Interpolation in z direction - which is the only ' );
    Writeln ( ' possible direction in this case - is not possible ' );
    Zextend := false

```

```

  end;

```

```

end;

```

```

If (Bad[I,J-1] = 5.0) then begin

```

```

  Writeln ( ' Point ',I:3,' ',J-1:3,' has also exp. error' );
  Writeln ( ' Therefore point ',I:3,' ',J-2:3,' will be used for ' );
  Writeln ( ' the interpolation of point ',I:3,' ',J:3);
  Writeln ( ' ');

```

```

  If (J >= 3) and ( Bad[I,J-2] <> 5.0 ) then begin

```

```

    Z_4 := Zdat[I,J-2]; X_4 := Xdat[I,J-2];
    Y_4 := Ydat[I,J-2]; V_4 := VVin[I,J-2]; B_4 := Beta[I,J-2];

```

```

  end

```

```

  else begin

```

```

    Writeln ( ' ');
    Writeln ( ' Interpolation in z direction - which is the only ' );
    Writeln ( ' possible direction in this case - is not possible ' );
    Zextend := false

```

```

  end;

```

```

end;

```

```

If ( I = 1 ) then

```

```

  Panel2alpha := -Arctan((Ydat[I,J]-Ydat[I+1,J])/(Xdat[I,J]-Xdat[I+1,J])) +
    ( 90.0 - 52.4 *PI/180.0

```

```

else

```

```
Panel2alpha := -Arctan((Ydat[I-1,J]-Ydat[I,J])/(Xdat[I-1,J]-Xdat[I,J])) +
  ( 90.0 - 52.4 ) * Pi / 180.0;
```

```
If ( B_3 = 0.0 ) then B_3 := B_4;
```

```
If ( B_4 = 0.0 ) then B_4 := B_3;
```

```
{ The following parameters are the flow angles relative to the normal
  vector of Panel2 at points I,J-1 and I,J+1 }
```

```
Pan2Beta3 := 0.5 * Pi - (B_3 + Panel2alpha );
```

```
Pan2Beta4 := 0.5 * Pi - (B_4 + Panel2alpha );
```

```
{ Calculating the velocity components normal and tangent to Panel2 }
```

```
Pan2V3_N := V_3 * Cos(Pan2Beta3);
```

```
Pan2V4_N := V_4 * Cos(Pan2Beta4);
```

```
Pan2V3_T := V_3 * Sin(Pan2Beta3);
```

```
Pan2V4_T := V_4 * Sin(Pan2Beta4);
```

```
{ Calculating the distances between points; will be used for
  interpolation }
```

```
deltax1 := Abs(-Zdat[I,J] + Z_3);
```

```
deltax2 := Abs(-Z_4 + Zdat[I,J]);
```

```
{ Linear interpolation for both components of velocity : ( For both
  components interpolation will be done in the z direction only ) }
```

```
V_N := ( Pan2V4_N - Pan2V3_N ) * deltax1 / ( deltax1 + deltax2 ) + Pan2V3_N;
```

```
V_T := ( Pan2V4_T - Pan2V3_T ) * deltax1 / ( deltax1 + deltax2 ) + Pan2V3_T;
```

```
If ( Zextend = False ) then begin
```

```
  If ( I = 1 ) then begin
```

```
    Writeln ( ' Interpolation in z direction only (since I = 1 ) but is );
```

```
    Writeln ( ' not possible; velocity and beta will be taken equal to );
```

```
    Writeln ( ' the ones at station 2,J );
```

```
    VVin[I,J] := VVin[I+1,J];
```

```
    Beta[I,J] := Beta[I+1,J];
```

```
  end
```

```
  else
```

```
  begin
```

```
    Writeln ( ' Interpolation in z direction only (since I = N ) but is );
```

```
    Writeln ( ' not possible; velocity and beta will be taken equal to );
```

```
    Writeln ( ' the ones at station N-1,J );
```

```
    VVin[I,J] := VVin[I-1,J];
```

```
    Beta[I,J] := Beta[I-1,J];
```

```
  end;
```

```
end
```

```
else
```

```
begin
```

```

( Calculating the average velocity : )

VVin[I,J] := Sqrt ( Sqr(V_M) + Sqr(V_I) );
Writeln ( ' Resultant velocity from interpolation : ', VVin[I,J]:12:6);

( Calculating the flow angle at this point : )

Beta[I,J] := 0.5*Pi - arctan ( V_I/V_M ) - Panel2alpha;
Writeln ( ' Resultant flow angle from interpolation : ', Beta[I,J]:12:6);
Writeln ( ' Press any key to continue ...');
Repeat until KeyPressed;

end;

end;
end;

I := I + 1;
end;
end;

Clrscr;

( End of the interpolation procedure for points where experimental error
is present

Calculating the angle between horizontal axis and each panel and then
determining the flow angle relative to the normal vectors of the panels
at the corners of each panel; finally calculating the flow rate (m3/A)/
(m3 passage/A passage) normal to each panel at the corners of the panel ;
Panel corner numbering, on top view of the panel :
1 - right lower corner
2 - right upper corner
3 - left lower corner
4 - left upper corner (see sketch))

For I := 1 to N-1 do begin
  For J := 1 to M-1 do begin
    Panelalpha := -Arctan((Ydat[I,J]-Ydat[I+1,J])/(Xdat[I,J]-Xdat[I+1,J]))
      + (90.0 - 52.4)*Pi/180.0;

    PanBeta[I,J,1] := 0.5*Pi - (Beta[I,J] + Panelalpha );
    PanBeta[I,J,2] := 0.5*Pi - (Beta[I+1,J] + Panelalpha );
    PanBeta[I,J,3] := 0.5*Pi - (Beta[I,J+1] + Panelalpha );
    PanBeta[I,J,4] := 0.5*Pi - (Beta[I+1,J+1] + Panelalpha );
    VPanel[I,J,1] := VVin[I,J]*Cos(PanBeta[I,J,1]);
    VPanel[I,J,2] := VVin[I+1,J]*Cos(PanBeta[I,J,2]);
    VPanel[I,J,3] := VVin[I,J+1]*Cos(PanBeta[I,J,3]);
    VPanel[I,J,4] := VVin[I+1,J+1]*Cos(PanBeta[I,J,4]);

    end;
  end;

  For I := 1 to N-1 do begin

```

For J := 1 to N-1 do begin

```
VPanel[I,J,1] := VPanel[I,J,1]*Density[I,J];
VPanel[I,J,2] := VPanel[I,J,2]*Density[I+1,J];
VPanel[I,J,3] := VPanel[I,J,3]*Density[I,J+1];
VPanel[I,J,4] := VPanel[I,J,4]*Density[I+1,J+1];
```

end;

end;

{ After the above loop, VPanel variables will include $(m'/A) / (m'psg/\Delta psg)$ normal to the panel

Calculating the mass flow rate through each panel
(nondimensionalized by the passage mass flow rate)

For the calculation of the mass flow rate through each panel linear variation assumption will be used: the panel will be divided into two triangles and the mass flow rate through each triangle will be taken as a plane in the dimensions s (direction along centerline), z (spanwise direction across the gap) and m' .

For I := 1 to N-1 do begin

For J := 1 to N-1 do begin

```
Z1 := Zdat[I,J]; Z2 := Zdat[I,J+1];
V1 := 0.0;
X21 := ( -Panelxy[I,J]/( Zdat[I,J+1] - Zdat[I+1,J] ) );
X22 := ( -Panelxy[I,J]/( Zdat[I,J+1] - Zdat[I+1,J] ) ) *
      (-Zdat[I,J+1]);
```

{ For triangle 123 :

```
X1 := 0.0;
triangle := 1;
```

```
vector1[1] := VPanel[I,J,1]-VPanel[I,J,2];
vector1[2] := -Panelxy[I,J];
vector1[3] := 0.0; - { = Zdat[I,J] - Zdat[I+1,J] }
vector2[1] := VPanel[I,J,1]-VPanel[I,J,3];
vector2[2] := 0.0; { = Xdat[I,J] - Xdat[I,J+1] }
vector2[3] := Zdat[I,J] - Zdat[I,J+1];
vectorn[1] := vector2[3]*vector1[2] - vector2[2]*vector1[3];
vectorn[2] := vector2[1]*vector1[3] - vector2[3]*vector1[1];
vectorn[3] := vector2[2]*vector1[1] - vector2[1]*vector1[2];
```

```
ACF[1] := vectorn[1]; ACF[2] := vectorn[2]; ACF[3] := vectorn[3];
ACF[4] := -( vectorn[1]*VPanel[I,J,1] + vectorn[2]*X1 +
              vectorn[3]*Zdat[I,J] );
```

{ ACF includes the coefficients of the triangle 123 plane eqn. :

```
ACF[1]*V + ACF[2]*X + ACF[3]*Z + ACF[4] = 0.0 }
```

```
Gaussn ( ACF, X1, X21, X22, Z1, Z2, V1, Integ123, triangle);
```

```
{ For triangle 234 : }
```

```
  X1 := Panelxy[I,J];  
  triangle := 2;
```

```
  vector1[1] := VPanel[I,J,2]-VPanel[I,J,3];  
  vector1[2] := Xdat[I+1,J] - Xdat[I,J+1];  
  vector1[3] := Zdat[I+1,J] - Zdat[I,J+1];  
  vector2[1] := VPanel[I,J,2]-VPanel[I,J,4];  
  vector2[2] := 0.0; { = Xdat[I+1,J] - Xdat[I+1,J+1] }  
  vector2[3] := Zdat[I+1,J] - Zdat[I+1,J+1];  
  vectorn[1] := vector2[3]*vector1[2] - vector2[2]*vector1[3];  
  vectorn[2] := vector2[1]*vector1[3] - vector2[3]*vector1[1];  
  vectorn[3] := vector2[2]*vector1[1] - vector2[1]*vector1[2];
```

```
  ACF[1] := vectorn[1]; ACF[2] := vectorn[2]; ACF[3] := vectorn[3];  
  ACF[4] := -( vectorn[1]*VPanel[I,J,2] + vectorn[2]*X1 +  
               vectorn[3]*Zdat[I+1,J]);
```

```
{ ACF includes the coefficients of the triangle 234 and will be  
  used in included file Gaussn }
```

```
Gaussn ( ACF, X1, X21, X22, Z1, Z2, V1, Integ234, triangle);
```

```
{ Calculating the panel area }
```

```
  Panels := (Zdat[I,J+1] - Zdat[I,J]);  
  Area := Panelxy[I,J]*Ppanels;
```

```
  HPanel[I,J] := (Integ123 + Integ234)/Area;
```

```
{ HPanel[I,J] = (m'panel/Δpanel)/(m'pasg/Δpasg) }
```

```
  Htip := Htip + HPanel[I,J]*Area;
```

```
If ( J = N-1 ) then begin  
  Areasum2 := 0.0;
```

```
  For JJ := 1 to N-1 do begin  
    Panels := (Zdat[I,JJ+1] - Zdat[I,JJ]);  
    Area := Panelxy[I,JJ]*Ppanels;  
    Mass_stn[I] := Mass_stn[I] + HPanel[I,JJ]*Area;  
    Areasum2 := Areasum2 + Area;  
  end;
```

```
  Mass_stn[I] := Mass_stn[I]/Areasum2;
```

```
{ The total mass flow rate at each chordwise station; will be used for  
  plotting the chordwise mass flow rate distribution }
```

```
end;
```

```

Areasum := Areasum + Area;

end;
end;

Mtip := Mtip/Areasum;

{ Mtip is the total mass flow rate through the gap nondimensionalized
  by the passage mass flow rate ( $\dot{m}/A_{gap}$ )/( $\dot{m}_{pass}/A_{pass}$ ) }

{ Determining the mass flow rate at each station where a three-hole probe
  measurement was taken; will be used together with the total pressure loss
  coefficients at these points to determine the mass averaged total pressure
  loss distribution. In order to determine the mass flow rate at a point I,J
  a panel will be formed joining the 4 adjacent points to point I,J and the
  normal direction of this panel will be used as the mass flow rate
  direction }

Assign (outfile3,outfil3);
Rewrite (outfile3);

For I := 1 to N do begin
  For J := 2 to M-1 do begin

    { If point I,J is at the leading edge of the measurement grid }

    If ( I = 1 ) then
      Panel2alpha := -Arctan((Ydat[I,J]-Ydat[I+1,J])/(Xdat[I,J]-Xdat[I+1,J])) +
        ( 90.0 - 52.4 ) * Pi / 180.0;

    { If point I,J is at the trailing edge of the measurement grid }

    If ( I = N ) then
      Panel2alpha := -Arctan((Ydat[I-1,J]-Ydat[I,J])/(Xdat[I-1,J]-Xdat[I,J])) +
        ( 90.0 - 52.4 ) * Pi / 180.0;

    { For other regular points within the grid }

    If ( I > 1 ) and ( I < N ) then
      Panel2alpha := -Arctan((Ydat[I-1,J]-Ydat[I+1,J])/(Xdat[I-1,J]-
        Xdat[I+1,J])) + ( 90 - 52.4 ) * Pi / 180.0;

    { Calculating the ( $\dot{m}/A$ )/( $\dot{m}_{pass}/A_{pass}$ ) in this normal direction at point I,J }

    Qnorm := VVin[I,J]*Density[I,J]*Cos(0.5*Pi - ( Beta[I,J] + Panel2alpha ));

    WriteLn (outfile3,Qnorm:16:13);
    end;
  end;

Close (outfile3);

{ Calculating the midpoints of the panels for plotting purposes : }

```

```

For I := 1 to M-1 do begin
  For J := 1 to M-1 do begin
    Xdat[I,J] := (Xdat[I,J] + Xdat[I+1,J])/2.0;
    Zdat[I,J] := (Zdat[I,J] + Zdat[I,J+1])/2.0;
    Ydat[I,J] := (Ydat[I,J] + Ydat[I,J+1])/2.0;
  end;
end;

{ Writing the results to output file }

Assign(outfile1, outfile1);
rewrite(outfile1);
Writeln(outfile1, ' X, Y and Z are the panel midpoint co-ordinates in (mm.) ');
Writeln(outfile1, ' X axis is tangent to the pressure side of the blade ');
Writeln(outfile1, ' Z is zero at the blade tip ');
Writeln(outfile1, ' ');
Writeln(outfile1, ' Tip Clearance (t/c) = ', tipclr:7:4);
Writeln(outfile1, ' ');
Writeln(outfile1, ' Re (based on test rig inlet velocity and blade chord) ');
Writeln(outfile1, ' Re = ', Re:15:2);
Writeln(outfile1, ' ');
Writeln(outfile1, ' I increases towards trailing edge ');
Writeln(outfile1, ' J increases towards the endwall ');
Writeln(outfile1, ' ');
Writeln(outfile1, ' Panel Number      X      Y      Z      (m/A)/(m.pasg/Aspg) ');
Writeln(outfile1, ' I      J ');
Writeln(outfile1, ' ----- ');
Writeln(outfile1, ' ');
  For I := 1 to M-1 do begin
    For J := 1 to M-1 do begin
      Writeln (outfile1, ' I:3, J:3, Xdat[I,J]:5:2, Ydat[I,J]:5:2, Zdat[I,J]:5:2, NPanel[I,J]:8:6);
      If ( J = M-1 ) then begin
        Writeln(outfile1, ' ');
        Writeln (outfile1, ' total (m/A)/(m.pasg/Aspg) at stn. ', I:3, ' ');
        Mass_stn[I]:14:11);
        Writeln (outfile1, ' ');
      end;
    end;
  end;
  Writeln (outfile1, ' ');
  Writeln (outfile1, ' (m.gap/Agap)/(m.pasg/Aspg) = ', Ntip:8:6);
  Writeln (outfile1, ' ');
  Writeln (outfile1, ' Total gap area along center line (mm2) = ', Areasum:15:4);
  Close(outfile1);

Assign (outfile2,outfil2);
Rewrite (outfile2);
  For I := 1 to M-1 do Writeln (outfile2,Mass_stn[I]:15:13);
  Close (outfile2);

end.

```



```

end;

Function BO(J : Integer; X : VEC) : Real;
{ Upper limits; as above. }
begin
  case J of
    3 : BO := -( ACP[4] + ACP[3]*X[1] + ACP[2]*X[2])/ACP[1];
    2 : If ( triangle = 1 ) then BO := X21*X[1] + X22 else BO := X1;
    1 : BO := Z2
  end
end;

Function GIN(M : Integer; NS : INDEX) : Real;
{ M is actual dimension, so 1 <= M <= NO.
  NS[J] is the number of subintervals in dimension J. }

var
  A, H, SUM, X : VEC; { SN[J] is the current
  SN, AN : INDEX;      { Subinterval No. in dim. J. }
                    { AN[J] is the current Abscissa No. for the
                    { Gaussian sum within the current subinterval. }

procedure SETUP(L : Integer);

var JJ : Integer;

begin
  for JJ := L to M do
    begin
      A[JJ] := AO(JJ, X);
      H[JJ] := (BO(JJ, X) - A[JJ])/NS[JJ];
      { Current subinterval length in dim. J }
      X[JJ] := A[JJ] + U[1]*H[JJ];
      { Current abscissa in dim. J }

      SUM[JJ] := 0;
      SN[JJ] := 1;
      AN[JJ] := 1;
    end;
  J := M
end; { SETUP }

begin { GIN }
  SUM[M+1] := 1;
  H[M+1] := 1;
  SETUP(1);
  repeat
    SUM[J] := SUM[J] + (SUM[J+1]*H[J+1])*(W[AN[J]]*F(J, X));
    if AN[J] < RULE then
      begin { Advance to next abscissa. }
        AN[J] := AN[J] + 1;
        X[J] := A[J] + U[AN[J]]*H[J];
        if J < M then SETUP(J+1)
        end
      end
    else if SN[J] < NS[J] then

```

```

begin                                { Advance to next subinterval. }
  A[J] := A[J] + H[J];
  SN[J] := SN[J] + 1;
  AN[J] := 1;
  X[J] := A[J] + U[AN[J]]*H[J];
  if J < N then SETOP(J+1)
end
else J := J - 1
until J = 0;
GIN := SUM(1)*H(1)
end; { GIN }

```

```

begin { GAUSSN }
  U[1] := 0.069431844202974; W[1] := 0.173927422568727;
  U[2] := 0.330009478207572; W[2] := 0.326072577431273;
  U[3] := 0.669990521792428; W[3] := 0.326072577431273;
  U[4] := 0.930568155797026; W[4] := 0.173927422568727;

```

```

  NS[1] := 1; NS[2] := 1; NS[3] := 1;

```

```

  Integ := GIN(N,NS);

```

```

end;

```

APPENDIX H

Source Code of the Leakage Model Programs

H.1 - Booth's Model

H.2 - Modified Simple Model

The inputs for these programs are the raw blade surface pressure data (output of the blade pressure data acquisition program) and the total tip gap mass flow rate (output of the actual mass flow rate calculation program). In addition to these inputs, program H.1 also requires a discharge coefficient value. The program is run for different discharge coefficient values until the calculated mass flow rate matches the actual one. This iteration could not be included into the program since 640 Kb. computer memory was not enough. Outputs of these programs are the "predicted" tip gap mass flow rate, resultant velocity and flow angle distributions along the blade chord (for program H.2 the value of the discharge coefficient is also an output).

The programs have been coded in Turbo Pascal and are to be compiled on an IBM compatible micro computer.

B.1

Program discharge;

(TIP LEAKAGE MODEL PROPOSED BY BOOTH ET AL. (1982))

type

coefmatrix = array[1..200] of real;
array1 = array[1..2,1..40] of real;
array2 = array[1..40] of real;

label step1; label step2;

var

Cntrx, Cntry : array[1..60] of real; { Centerline station co-ordinates
where three-hole probe
measurements were taken }

surfxcrdn, surfyocrdn
: array[1..100] of real; { Blade suction surface co-ordinates }

Beta_Normal : array2; { the normal velocity (normal to centerline) angle
relative to the positive side of the x axis at
each blade pressure surface tap }

Psurfangle : array2; { Pressure surface angle relative
to the positive x direction;
pressure surface tangential velocity
will be in this direction }

Flow_Angle : array2; { Resulting flow angle in the gap at a particular
pressure surface tap }

surfx, surfy : array2; { suction surface & tip clearance straight stream
line meeting point }

Dens_Densin : array1; { density at measurement point /density at test
section inlet }

Done, Finished : boolean;

Areh_ary : array2;

Angle1, Angle2 : real; { Angle1 : Angle of line that joins the
front edge of the centerline segment to
the pressure side tap (relative to
positive side of x axis . Angle2 is similar for
the back edge of the centerline segment) }

Normalangle : real; { angle of the normal vector of the centerline
segment relative to the positive side of the x axis }

```

inp, inq      : real;      { initial transducer readings }
tapx, tapy    : array1;    { tap x and y co-ordinates }
q, Pin        : array1;    { q : contraction pressure difference
                             Pin : Test section inlet static pressure }
Ps_Pin, Ps     : array1;    { Ps : static pressure at the tap }
Pin_Patm       : array1;    { Pin - Patm will be obtained from
                             the curve Pin_Patm vs Psc1 - Psc2. }
VWin          : array1;

I, J, K, n, temporary : integer;
atmprs, DD     : real;
temperature, contrc, tipclr, Real_area : real;
Realmass       : array[1..36] of real; { chordwise distribution of the
                                         real mass flow rate obtained
                                         from the three-hole probe
                                         measurements }

Ixx, Yyy       : array[1..37] of real;
Reass_sum      : real;

infile1, infile2, infile3, infile4, infile5, outfile,
infile6, infile7, infile8, infile9, outfile2, outfile3, outfile4, outfile5,
outfile6, outfile7, outfile8, outfile9, outfile10 : text;
infil1, infil2, infil3, infil4, infil5, outfil,
infil6, infil7, infil8, infil9, outfil2, outfil3, outfil4, outfil5,
outfil6, outfil7, outfil8, outfil9, outfil10 : string[25];

Y1, Y2, Y3, Dummy1, Dummy2, Dummy3, n1, n2, c1, c2,
NVelocity, distance1, distance2, P, Cd, JVelocity, YVelocity,
line_slope, constant, PrevAngle, Prevangle1, NVelocity2 : real;
Area, Mass, Mass_sum, Area_sum, Mass_ratio, Mass_real : real;

Velocity       : array2; { Resultant velocity through the gap
                           at a particular pressure side tap location:
                           calculated using an iterative procedure }

V1, V2         : array2; { Velocities normal to the panel formed by the
                           points where resultant velocities at sequential
                           pressure surface taps cross the centerline }

Segment_alpha   : array2; { Angle of the above indicated panel relative
                           to the x axis which is tangent to the pressure
                           side of the blade }

X, Y, X2, F     : array2; { X,Y co-ordinates where the resultant velocity
                           crosses the centerline, X2 will be the mid
                           point of sequential cross points }

NX              : integer;
arrayps        : coeefmatrix;
naxps, nps     : integer;
Answer         : string[25];
NS, NP         : integer;

```

```

( NS      : Number of usable taps on the suction surface;
  NP      : Number of usable taps on the pressure surface )

const

    Pcf = 1.373; { calibration factor for transducer used for P-Ps
                  readings (Pa/mv) }
    Qcf = 1.428; { calibration factor for transducer used for
                  contraction pressure difference readings (Pa/mv) }
    {-----}

function eval(y : real ; array1 : coefmatrix ; maxdeg, n : integer) : real;

{ This function is used for extracting data from least-square fitted curve
  to Pin - Patm vs Psc1-Psc2 calibration }

var

    ib, ic, nl2, k, l : integer;
    dk, dkp1, dkp2    : real;

begin { beginning of function eval }

    ib := maxdeg + 1;
    ic := maxdeg + ib - 1;

    { evaluate n = 0, 1 as special cases }

    if (n = 0) then begin
        eval := array1[ic];
    end; { of the if statement }

    if (n = 1) then begin
        eval := array1[ic] + array1[ic+1]*(y-array1[1]);
    end; { of the if statement }

    if (n > 1) then begin
        dkp2 := array1[ic + n];
        dkp1 := array1[ic + n - 1] + (y - array1[n])*dkp2;
        nl2 := n-2;
        if(nl2 >= 1) then begin
            for l := 1 to nl2 do begin
                k := l+nl2-1;
                dk := array1[ic+k] + (y-array1[k+1])*dkp1 - array1[ib+k]*dkp2;
                dkp2 := dkp1;
                dkp1 := dk;
            end;
            eval := array1[ic] + (y-array1[1])*dkp1 - array1[ib]*dkp2;
        end;
    end;

end;

```

```
(-----)
```

```
begin { beginning of the main program }
```

```
temporary := 0;
```

```
NS = 32; NP = 30;
```

```
DD := 180.0/Pi; --
```

```
n := NS + NP;
```

```
Write (' Enter the real tip mass flow rate ( (m/A)/(m.pasg/A.pasg) ) : ');
```

```
Readln (Mass_real);
```

```
Writeln ('');
```

```
Write (' Enter the gap area (in mm2) corresponding to this mass flow rate : ');
```

```
Readln (Real_area);
```

```
Writeln ('');
```

```
Write (' Enter the input file name for blade surface pressures : ');
```

```
Readln (infil2);
```

```
Writeln ('');
```

```
Write (' Do you want to run the program for row 1 (closest to blade tip) : ');
```

```
Readln (Answer);
```

```
Writeln ('');
```

```
Write (' Enter the output file name for the first part of calculations : ');
```

```
Readln (outfil1);
```

```
Writeln ('');
```

```
Write (' Enter the output file name for the second part of calculations : ');
```

```
Readln (outfil2);
```

```
Writeln ('');
```

```
Writeln (' Enter output file name for x/c values that can be used for ');
```

```
Write (' plotting the resultant velocity and flow angle distribution ');
```

```
Readln (outfil3);
```

```
Writeln ('');
```

```
Writeln (' Enter output file name for x/c values that will be used for ');
```

```
Write (' plotting the mass flow rate and normal vel. distribution : ');
```

```
Readln (outfil8);
```

```
Writeln ('');
```

```
Write (' Enter output file name for normal velocity distribution : ');
```

```
Readln (outfil4);
```

```
Writeln ('');
```

```
Write (' Enter output file name for resultant velocity distribution : ');
```

```
Readln (outfil5);
```

```
Writeln ('');
```



```

Write (' Enter output file name for flow angles : ');
Readln (outfil6);
Writeln (' ');

Write (' Enter output file name for calculated gap mass flow rate distrb ');
Readln (outfil7);
Clrscr;

Writeln (' Enter output file name for panel areas over which linear ');
Write (' velocity distribution is assumed ');
Readln (outfil10);

Write (' Enter output file name for detailed check on mass flow rate calc. ');
Readln (outfil9);
Clrscr;

Writeln (' ');
Write (' Enter the tip clearance (t/c) : '); Readln (tipclr);
Writeln (' ');

Write (' Enter the discharge coefficient : ');
Readln (Cd);
Writeln (' ');

Clrscr;

If (Answer = 'N') or (Answer = 'n') then begin
Ns := Ns-2; infil1 := 'taps14.dat'; end else infil1 := 'taps1.dat';

    infil3 := 'array';
    infil4 := 'centerx';
    infil5 := 'centery';
    infil6 := 'prs_tap_ang';
    infil7 := 'ssrfcrdt';
    infil8 := 'Mass';
    infil9 := 'Cntxy';

    { The data from the following two files will be used to correct the real mass
      flow rate if the ideal flow rate cannot be calculated over the whole chord
      length }

Assign (Infile8, infil8);
Reset (Infile8);
  For I := 1 TO 36 do
    Readln (Infile8, Realmass[I]);
Close (Infile8);

Assign (Infile9, infil9);
Reset (Infile9);
  For I := 1 TO 37 do
    Readln (Infile9, dummy1, Ixx[I], Yyy[I]);
Close (Infile9);

```

```

Assign (infile4,infil4);
Reset (infile4);
  for I := 2 to 52 do
    Readln (infile4,Cntrx[I]);
  Close (infile4);

Clrscr;
Writeln(' Reading the centerline x co-ordinates is completed ');
Writeln(' ');

Assign (infile5,infil5);
Reset (infile5);
  for I := 2 to 52 do
    Readln (infile5,Cntry[I]);
  Close (infile5);

Writeln(' Reading the centerline y co-ordinates is completed ');
Writeln(' ');

      Cntrx[1] := 8.0e-03;
      Cntry[1] := 8.0e-03;
      Cntry[53] := 5.0e-03;
      Cntrx[53] := 1.01;

Assign (infile6,infil6);
Reset (infile6);
  for J := 1 to Np do begin
    Readln (infile6,Psurfangle[J]);
    Psurfangle[J] := -((Psurfangle[J] - (180.0+49.44))*Pi/180.0);
  end;
Close(infile6);

Writeln(' Reading the pressure surface slope is completed ');
Writeln(' ');

Assign (infile7,infil7);
Reset (infile7);
  for I := 1 to 66 do
    Readln (infile7,Dummy1,surfxcrdn[I],surfyocrdn[I]);
    { Only "suction" surface co-ordinates starting from the LEADING edge }
  Close (infile7);

Writeln(' Reading the blade suction surface co-ordinates is completed ');
Writeln(' ');

Assign (infile3,infil3);
Reset (infile3);
  Readln (infile3,naxps,nps);
  for J := 1 to 200 do
    Readln (infile3,arrayps[J]);
  Close (infile3);

```

```

Writeln(' Reading the array is completed ');
{ This array will be used to extract the inlet static pressure from the
  Pinlet - Patm & Psc1- Psc2 least square fitted curve }
Writeln(' ');

Assign (infile1,infil1);
Reset (infile1);
{ First the suction surface tap co-ordinates, later the pressure surface
  tap co-ordinates will be read ( Pressure surface taps are read starting
  from the trailing edge while it is the other way around for the suction
  surface ) }

I := 1;
For J := 1 to Ns do begin
  Readln (infile1,Dummy1, tapx[I,J], tapy[I,J]);
end;
I := 2;
For J := 1 to Np do begin
  Readln (infile1,Dummy1, tapx[I,J], tapy[I,J]);
end;
Close (infile1);

Writeln(' Reading the tap co-ordinates is completed ');
Writeln(' ');

Assign (infile2,infil2);
Reset (infile2);

Readln (infile2,inq); Readln (infile2,inp); Readln (infile2,temperature);
Readln (infile2,atmprs); Readln (infile2,contrc);
I := 1;
For J := 1 to Ns do begin
  Readln (infile2,Dummy1,Dummy2,Dummy3,q[I,J],Ps_Pin[I,J]);
end;
I := 2; J := Np+1;
While ( J >= 2 ) do begin
  J := J-1;
  Readln (infile2,Dummy1,Dummy2,Dummy3,q[I,J],Ps_Pin[I,J]);
end;
Close (infile2);

Writeln(' Reading the blade surface pressures is completed ');
Writeln(' ');
Clrscr;

{ Converting atmospheric pressure to Pa }

atmprs := (atmprs-0.7)*13.6*9.81*998.6/1000.0;

Assign (outfile,outfil);
Rewrite (outfile);

I := 1;

```

```

For J := 1 to Ns do begin

  { Determining the inlet dynamic pressure from the contraction pressure
    difference }

     $q[I,J] := (q[I,J] - inq) * Qcf * 1000;$ 

  { Calculating the inlet static pressure ; using the curve Ps-Patn
    vs Psc1-Psc2 }

     $Pin[I,J] := eval( q[I,J], arrayps, maxps, nps ) + ataprs;$ 

  { Calculating the inlet dynamic pressure using the contraction factor }

     $q[I,J] := q[I,J] * contrc;$ 

  { Converting the Ps_pin[I,J] reading from mv into Pa. }

     $Ps\_Pin[I,J] := (Ps\_Pin[I,J] - inp) * Pcf * 1000;$ 

  { Calculating the absolute value of the blade static pressures }

     $Ps[I,J] := Pin[I,J] + Ps\_Pin[I,J];$ 

  { Calculating the density ratio (assuming negligible temperature change) }

     $Dens\_Densin[I,J] := Ps[I,J] / Pin[I,J];$ 

  { Calculating the velocity ratio : }

     $VVin[I,J] := Sqrt( (1.0 / Dens\_Densin[I,J]) * ((q[I,J] - Ps\_Pin[I,J]) / q[I,J]) );$ 

  (-----)
  Writeln (outfile, 'J= ', J:3, ' Suction side VVin = ', VVin[I,J]:10:7);
end;
  Writeln (outfile, ' ');
  (-----)

  I := 2;

For J := 1 to Np do begin

   $q[I,J] := (q[I,J] - inq) * Qcf * 1000;$ 

  { Calculating the inlet static pressure ; using the curve Ps-Patn
    vs Psc1-Psc2 }

     $Pin[I,J] := eval( q[I,J], arrayps, maxps, nps ) + ataprs;$ 

  { Calculating the inlet dynamic pressure using the contraction factor }

     $q[I,J] := q[I,J] * contrc;$ 

```

```

{ Converting the Ps_pin[I,J] reading from mv. to Pa. }
    Ps_Pin[I,J] := (Ps_Pin[I,J]-inp)*Pcf*1000;

{ Calculating the absolute value of the blade static pressures }

    Ps[I,J] := Pin[I,J] + Ps_Pin[I,J];

{ Calculating the density ratio (Assuming temperature change is negligible) }

    Dens_Densin[I,J] := Ps[I,J]/Pin[I,J];

{ Calculating the velocity ratio }

    VVin[I,J] := Sqrt((1.0/Dens_Densin[I,J])*((q[I,J]- Ps_Pin[I,J])/q[I,J]));

{-----}
    Writeln (outfile,'J= ',J:3,' Pressure side VVin = ',VVin[I,J]:10:7);
end;
    Writeln (outfile,' ');
{-----}

    Writeln(' V/Vin values are calculated ');
    Writeln(' ');
    Writeln(' Calculating the normal velocity directions ...');
    Writeln(' ');

For J := 1 to NP do begin

    If( J = 15) then Clrscr;

    Writeln(' Tap number on the pressure surface : ',J:3);

    Done := false;

    For K := 1 to 52 do begin

        { Determine the normal velocity direction for each pressure side tap

            First calculating the angle of the lines joining the tap to the
            centerline segment edges relative to the x axis ( x axis is positive
            towards the trailing edge and is tangent to the pressure side of the
            blade ) ; the front edge of a segment is the one closer to the leading
            edge }

            If ( (Ctrx[K] - Tapx[2,J]) = 0.0 ) then
                Angle1 := Pi/2.0
            else
                Angle1 := Arctan((Cntry[K] - Tapy[2,J])/(Ctrx[K] - Tapx[2,J]));

            If ( (Ctrx[K+1] - Tapx[2,J]) = 0.0 ) then
                Angle2 := Pi/2.0
            else
                Angle2 := Arctan((Cntry[K+1] - Tapy[2,J])/(Ctrx[K+1] - Tapx[2,J]));

```

```

    { Calculating the angle between the normal of the segment and
      the positive side of the x axis }
    If ( (Cntry[K]-Cntry[K+1]) = 0.0 ) then
      Normalangle := Pi/2.0
    else
      Normalangle := Arctan(-(1.0/((Cntry[K] - Cntry[K+1])/
        (Cntrx[K] - Cntrx[K+1]))));

    If ( Angle1 < 0.0 ) or (( Cntry[K] < Tapy[2,J] ) and
      ( Cntrx[K] < Tapx[2,J] )) then Angle1 := Angle1 + Pi;

    If ( Angle2 < 0.0 ) or (( Cntry[K+1] < Tapy[2,J] ) and
      ( Cntrx[K+1] < Tapx[2,J] )) then Angle2 := Angle2 + Pi;

    If ( Normalangle < 0.0 ) then Normalangle := Pi + Normalangle;

    If (( Normalangle < Angle1 ) and ( Normalangle > Angle2 )) or
      (( Normalangle > Angle1 ) and ( Normalangle < Angle2 )) then begin
      -----
      Writeln (outfile, ' Normal velocity direction calculation ');
      Writeln (outfile, ' Velocity vector originating from tap ',J:3);
      Writeln (outfile, ' Tap co-ordinates : ',Tapx[2,J], ', ',Tapy[2,J]);
      Writeln (outfile, ' is normal to centerline segment which is ');
      Writeln (outfile, ' between stations : ',K:3, ' and ',K+1:3);
      Writeln (outfile, ' Station ',K:3, ' coordinates : ',Cntrx[K], ', ',Cntry[K]);
      Writeln (outfile, ' Station ',K+1:3, ' coordinates : ',Cntrx[K+1],
        ', ',Cntry[K+1]);
      Writeln (outfile, ' Angle1= ',Angle1*DD:10:7, ' Angle2= ',Angle2*DD:10:7);
      Writeln (outfile, ' Normal angle of this segment : ',Normalangle*DD:10:7);
      Writeln (outfile, ' ');
      -----
      Beta_normal[J] := Normalangle; Done := true; Goto step1;
    end;

    { If the line is normal to the center line between two segments : }

    If ( K > 1 ) and
      (( PrevAngle-Prevangle1)*(Normalangle-Angle1) < 0.0 ) then begin

      Write ( ' Point is normal to the center line between ' );
      Writeln ( ' two segments ' );

      Write (outfile, ' Point is normal to the center line between ');
      Writeln (outfile, ' two segments ');

      Beta_normal[J] := Angle1; Done := True; Goto step1; end;

      PrevAngle := Normalangle; PrevAngle1 := Angle1;
    end;

step1:

```

end;

```
Close(outfile);
```

```

WriteLn (' Calculation of the normal velocity directions is completed ');
WriteLn (' ');
WriteLn (' Beginning      to iteration for normal velocity magnitude ');
WriteLn (' ');
WriteLn (' Press any key to continue ... ');
Repeat Until KeyPressed;

```

```
Assign (outfile2,outfil2);
Rewrite (outfile2);
```

```
Clrscr; J := NP+1;
```

```
While ( J >= 2 ) do begin
```

J := J-1; Finished := False;

```

{-----}
Writeln (outfile2, ' ');
Writeln (outfile2, ' Tap # ', J:3);
Writeln (outfile2, ' Tap co-ordinates ; Tapx/c : ', Tapx[2,J]:10:5, ' Tapy/c : ',
        Tapy[2,J]:10:5);
{-----}

```

```

NVelocity := VVin[2,J]; { Velocity normal to centerline; as a beginning
                           value will be taken equal to pressure side
                           tangential velocity }

```

Repeat

{ Resultant flow angle and velocity magnitude at this tap location }

```

Velocity := VVin[2,J]*Cos(Psurfangle[J]) + NVelocity*Cos(Beta_Normal[J]);
Yvelocity := VVin[2,J]*Sin(Psurfangle[J]) + NVelocity*Sin(Beta_Normal[J]);
Flow_angle[J] := arctan( Yvelocity/Xvelocity );
Velocity[J] := Sqrt( Sqr(Xvelocity) + Sqr(Yvelocity) );

```

```

{-----}
Writeln (outfile2, ' ');
Writeln (outfile2, 'NVelocity/Vin = ', NVelocity:10:7);
Writeln (outfile2, 'Pressure surface angle = ', Psurfangle[J]*DD:10:5);
Writeln (outfile2, 'Normal velocity direction = ', Beta_Normal[J]*DD:10:5);
Writeln (outfile2, 'XVelocity/Vin = ', XVelocity:10:7, ' YVelocity/Vin = ',
YVelocity:10:7);
Writeln (outfile2, 'Flow angle : ', Flow_angle[J]*DD:10:5);
Writeln (outfile2, 'Resultant Velocity/Vin : ', Velocity[J]:10:7);
{-----}

```

[Determining the location where the straight line crosses the suction

```

surface edge : }

    line_slope := Yvelocity/Xvelocity;
    constant := (tapy[2,J]- line_slope*tapx[2,J]);

{ Determining the suction surface point which satisfies the equation :
y = line_slope*x + constant }

    K := 1; Done := False;

While ( (K <= 65) and (Done = False) ) do begin

    If ( (surfxcrdn[K]-tapx[2,J]) = 0.0 ) then
        Y1 := Pi/2.0
    else begin
        Y1 := arctan( (surfyocrdn[K]-tapy[2,J])/(surfxcrdn[K]-tapx[2,J]) );
        If ( surfyocrdn[K] < Tapy[2,J] ) and ( surfxcrdn[K] < Tapx[2,J] )
            then Y1 := Y1 + Pi;
    end;

    If ( (surfxcrdn[K+1]-tapx[2,J]) = 0.0 ) then
        Y2 := Pi/2.0
    else begin
        Y2 := arctan( (surfyocrdn[K+1]-tapy[2,J])/(surfxcrdn[K+1]-tapx[2,J]) );
        If ( surfyocrdn[K+1] < Tapy[2,J] ) and ( surfxcrdn[K+1] < Tapx[2,J] )
            then Y2 := Y2 + Pi;
    end;

    If ( Y1 < 0.0 ) then Y1 := Pi + Y1;
    If ( Y2 < 0.0 ) then Y2 := Pi + Y2;
    If ( Flow_angle[J] < 0.0 ) then
        Flow_angle[J] := Pi + Flow_angle[J];

    If ( (Flow_angle[J] < Y1) and (Flow_angle[J] > Y2) ) or
        ( (Flow_angle[J] > Y1) and (Flow_angle[J] < Y2) ) then begin

        { The resultant velocity will cross the suction surface edge between
        points K and K+1 ; the equation for this segment of the suction
        surface is y = m1*x + c1 }

        {-----}
        Writeln (outfile2, 'The velocity will cross the suction surface edge of ');
        Writeln (outfile2, 'the clearance between surface points K= ',K:3, ' and ',
            K+1:3);
        {-----}

        Done := True;
        m1 := (surfyocrdn[K]-surfyocrdn[K+1])/(surfxcrdn[K]-surfxcrdn[K+1]);
        c1 := -surfxcrdn[K]*m1 + surfyocrdn[K];

        { Co-ordinates of the suction surface - velocity direction cross point : }

        surfx[J] := (c1-constant)/(line_slope-m1);
        surfy[J] := line_slope*surfx[J] + constant;
    end;

```



```

      K := K+1;
end; { for the while statement }

If ( Done = False ) then begin
{-----}
  Writeln (outfile2, ' Flow direction - suction surface meeting point ');
  Writeln (outfile2, ' could not be determined');
{-----}

{ This may happen close to the trailing edge; then, since the velocity
  does not cross the centerline, it will not be considered in the mass flow
  calculation. }

      NX := J+1; Goto step2;

end else begin
      NX := 1;
{-----}
  Writeln (outfile2, ' Flow direction-suction surface cross point : ');
  Writeln (outfile2, ' X/C = ', surfx[J]:10:5, ' Y/C = ', surfy[J]:10:5);
{-----}

  end;

{ Suction surface meeting point will be surfx[J] and surfy[J];
  now, calculating the static pressure at this point by linear interpolation
  between the two suction surface taps on both sides of this point }

  K := 1; Done := False;
  While ( (K <= Ns-1) and ( Done = False )) do begin

    If (( tapx[1,K] < surfx[J] ) and ( tapx[1,K+1] > surfx[J] ))
      or (( tapx[1,K] > surfx[J] ) and ( tapx[1,K+1] < surfx[J] )) then begin

      { Interpolating the static pressure : }

      distance1 := Sqrt( Sqr(tapx[1,K]-sux[J]) + Sqr(tapy[1,K]-suy[J]) );
      distance2 := Sqrt( Sqr(tapx[1,K]-tapx[1,K+1]) +
        Sqr(tapy[1,K]-tapy[1,K+1]) );

      P := -( Ps[1,K] - Ps[1,K+1] ) * distance1 / distance2 + Ps[1,K];
      Done := True;
{-----}
      Writeln (outfile2, ' Point X,Y is between suction surface taps ', K:3, ' and ', K+1:3);
      Writeln (outfile2, ' And the interpolated static pressure at this point is ');
      Writeln (outfile2, ' Ps (Pa) = ', P:13:8);
{-----}

    end ;

    If ( surfx[J] < -0.00475 ) then begin

      P := Ps[1,2]; Done := true;
    end;

```

```

K := K + 1;
end;

If ( Done = false ) then begin
{-----}
  Writeln (outfile2, ' The taps on either side of point X,Y could not be ');
  Writeln (outfile2, ' determined; therefore interpolation of the ');
  Writeln (outfile2, ' static pressure is not performed for point X,Y ');
{-----}

  NX := J+1; Goto step2;
end;

{ Having the static pressure at this point, calculating the new normal
  velocity by applying the Bernoulli equation with a discharge coefficient }

  NVelocity2 := Cd*Sqrt( (Ps[2,J]-P)/(dens_densin[2,J]*q[2,J]) );

{-----}
  Writeln (outfile2, ' NVelocity2/Vin : ',NVelocity2:10:7);
{-----}

  ( Comparing this new value with the previous one : )

  If ( (NVelocity2/NVelocity < 1.01) and (NVelocity2/NVelocity > 0.99) ) then
    begin
      Finished := True;
    {-----}
      Writeln (outfile2, ' Further iteration is not necessary ');
      Writeln (outfile2, ' ');
      Writeln (outfile2, ' ');
      Writeln (outfile2, ' ');
    {-----}
      end else begin
    {-----}
      Writeln (outfile2, ' Further iteration is necessary ');
      Writeln (outfile2, ' since NVelocity2/NVelocity = ',NVelocity2/NVelocity:10:7);
      Writeln (outfile2, ' ');
    {-----}
      NVelocity := (NVelocity2 + NVelocity)/2.0
    end;

  Until ( Finished = True );

end;

Step2:

Writeln ( ' The iteration procedure for the normal v. is completed' );

{ Determining the point where the resultant velocity across the gap

```

(at an angle of Flow_angle[J] and magnitude of Velocity[[J]) crosses
the centerline : }

```
{-----}
Writeln (outfile2, ' ');
Writeln (outfile2, ' ');
Writeln (outfile2, ' ');
Writeln (outfile2, ' Determining the point where the resultant velocity is ');
Writeln (outfile2, ' crossing the centerline');
{-----}
```

For J := NX to NP do begin

```
    line_slope := Sin(Flow_Angle[J])/Cos(Flow_Angle[J]);
    Constant := (tapy[2,J] - line_slope*tapx[2,J]);
    { Determining the center line point which satisfies the equation
      y = line_slope*x + constant }
    {-----}
    Writeln (outfile2, ' Tap # on the pressure surface : ', J:3);
    {-----}
```

K := 1; Done := False;
While ((K <= 52) and (Done = False)) do begin

```
    If ( Cntrx[K]-tapx[2,J] = 0.0) then
        Y1 := Pi/2.0
    else begin
        Y1 := arctan( (Cntry[K]-tapy[2,J])/(Cntrx[K]-tapx[2,J]) );
        If ( Cntry[K] < Tapy[2,J] ) and ( Cntrx[K] < Tapx[2,J] )
            then Y1 := Y1 + Pi;
    end;

    If ( (Cntrx[K+1]-tapx[2,J]) = 0.0) then
        Y2 := Pi/2.0
    else begin
        Y2 := arctan( (Cntry[K+1]-tapy[2,J])/(Cntrx[K+1]-tapx[2,J]) );
        If ( Cntry[K+1] < Tapy[2,J] ) and ( Cntrx[K+1] < Tapx[2,J] )
            then Y2 := Y2 + Pi;
    end;
```

```
    If ( Y1 < 0.0 ) then Y1 := Pi + Y1;
    If ( Y2 < 0.0 ) then Y2 := Pi + Y2;
    If ( Flow_angle[J] < 0.0 ) then
        Flow_angle[J] := Pi + Flow_angle[J];
```

```
    If ( (Flow_angle[J] < Y1) and (Flow_angle[J] > Y2) ) or
        ( (Flow_angle[J] > Y1) and (Flow_angle[J] < Y2) ) then begin
```

```
        { The meeting point will be on segment K which joins the centerline
          stations K and K+1
          Coefficients of the line in the Flow_angle direction and passing
          through tap [2,J] (pressure side tap J ) are "line_slope" and "constant"
        }
```

```

        Done := True;
        m2 := (Cntry[K]-Cntry[K+1])/(Cntrx[K]-Cntrx[K+1]);
        c2 := -Cntrx[K]*m2 + Cntry[K];

        { co-ordinates where these two lines cross each other (ie. the point
          where the normal velocity at tap[2,J] crosses the centerline ) : }

        X[J] := (c2-constant)/(line_slope-m2);
        Y[J] := line_slope*X[J] + constant;
    end;
    K := K+1;
end;

If ( Done = False ) then begin
{-----}
    Writeln (outfile2, ' Flow direction - center line meeting point ');
    Writeln (outfile2, ' could not be determined ');
{-----}
    temporary := J+1;
end else begin
{-----}
    Writeln (outfile2, ' The cross point will be on centerline segment which ');
    Writeln (outfile2, ' joins stations : ',K-1:3, ' and ',K:3);
    Writeln (outfile2, ' Cross point co-ordinates/C : ',X[J]:10:5,
            ', ',Y[J]:10:5);
    Writeln (outfile2, ' ');
{-----}

    end;
end; { for the J for-do loop }

Close(outfile2);

Assign (outfile9,outfil9);
Rewrite (outfile9);

Writeln ('Resultant velocity - centerline cross point co-ordinates are calculated');

If (temporary <> 0) then NX := temporary;

{ The following section of the program makes sure that the considered gap area
  is the same for both the real and the ideal mass flow rates (due to the
  procedure used in the ideal mass flow rate calculation, the flow rate through
  a small region close to trailing edge may not be determined )

  If ( NX > 1 ) Then begin
    Rmass_sum := 0.0; Area_sum := 0.0;
    done := false;
    Writeln (' ');
    Writeln (' The last velocity vector centerline cross point co-ordinates ');
    Writeln (' are X = ',X[NX]:10:5, ' Y = ',Y[NX]:10:5);

    For I := 1 to 37 do begin

```

```

If ( done = false ) then begin
  If ( Xxx[I]/250.0 > X[NX] ) then begin
    Writeln ( ' ');
    Writeln ( ' The first centerline station used for TRP measurements ');
    Writeln ( ' downstream of the last cross point used in ideal calculation ',
      ' is : ', Xxx[I]/250.0);
    Rmass_sum := Rmass_sum + ((Xxx[I]-X[NX]*250.0)/(Xxx[I]-Xxx[I-1]))*
      Realmass[I-1]*Sqrt ( Sqr(Xxx[I]-X[NX]*250.0) +
        Sqr(Yyy[I]-Y[NX]*250.0) )*250.0*tipclr;
    Area_sum := Area_sum + Sqrt ( Sqr(Xxx[I]-X[NX]*250.0) +
      Sqr(Yyy[I]-Y[NX]*250.0) )*250.0*tipclr;
    done := true ;
    For J := I to 36 do begin
      Area := Sqrt ( Sqr(Xxx[J]-Xxx[J+1]) + Sqr(Yyy[J]-Yyy[J+1]) )*250.0*tipclr;
      Rmass_sum := Rmass_sum + Realmass[I]*Area;
      Area_sum := Area_sum + Area;
      Writeln ( ' The total area for which the real mass flow rate will ');
      Writeln ( ' not be considered is ', Area_sum*10.5);
    end;
  end;
end;
end;
end;
end;

```

```

Mass_real := (Mass_real*Real_area - Rmass_sum)/(Real_area-Area_sum);
Real_area := Real_area - Area_sum;

```

```

Area_sum := 0.0; Mass_sum := 0.0;

```

```

For J := NX to NP-1 do begin
  Segment_alpha[J] := arctan((Y[J+1]-Y[J])/(X[J+1]-X[J]));
  Writeln(outfile9, ' X[J] = ', X[J]:10:5, ' Y[J] = ', Y[J]:10:5);
  Writeln (outfile9, ' X[J+1] = ', X[J+1]:10:5, ' Y[J+1] = ', Y[J+1]:10:5);
  If (J+1 > Ns) then Dens_Densin[1,J+1] := Dens_Densin[1,J];
  V1[J] := Dens_Densin[1,J]*Velocity[J]*Sin(Flow_angle[J]-Segment_alpha[J]);
  V2[J] := Dens_Densin[1,J+1]*Velocity[J+1]*Sin(Flow_angle[J+1]-
    Segment_alpha[J]);
  Area := Sqrt ( Sqr(X[J]-X[J+1]) + Sqr(Y[J]-Y[J+1]) )*250.0*tipclr*250.0;
  Area_ary[J] := Area;
  F[J] := (V1[J]+V2[J])/2.0;
  Y[J] := (Velocity[J]*Sin(Flow_angle[J]-Segment_alpha[J])+
    Velocity[J+1]*Sin(Flow_angle[J+1]-Segment_alpha[J]))/2.0;
  X2[J] := (X[J] + X[J+1])/2.0;
  Mass := Area*(V1[J]+V2[J])/2.0;
  Mass_sum := Mass_sum + Mass;
  Area_sum := Area_sum + Area;
  Writeln (outfile9, ' J= ', J:3, ' Segment alpha= ', Segment_alpha[J]*DD:10:5,
    ' V1[J]= ', V1[J]:10:5, ' V2[J]= ', V2[J]:10:5);
  Writeln (outfile9, ' Velocity J = ', Velocity[J]:10:5);
  Writeln (outfile9, ' Velocity J+1 = ', Velocity[J+1]:10:5);
  Writeln (outfile9, ' Area = ', Area:10:5, ' Flow_angle= ', Flow_angle[J]*DD:10:5);
  Writeln (outfile9, ' Mass= ', Mass:10:5);
  Writeln (outfile9, ' X[J]= ', X[J]:10:5, ' Y[J]= ', Y[J]:10:5, ' F[J]= ', F[J]:10:5);

```

```

      Writeln (outfile9, ' density[1,J] = ',Dens_Densin[1,J]);
      Writeln (outfile9, ' density[1,J+1] = ',Dens_Densin[1,J+1]);
      Writeln (outfile9, ' ');
      Writeln (outfile9, ' ');
    end;

    Mass_ratio := Mass_sum/(Mass_real*Real_area);

    For J := NX to NP-1 do
      Area_ary[J] := Area_ary[J]/Area_sum;

      {-----}
      Writeln (outfile9, ' ');
      Writeln (outfile9, ' total gap area = ',area_sum:10:5);
      Writeln (outfile9, ' Cd= ',Cd:10:6);
      Writeln (outfile9, ' IDEAL (mass.gap/A.gap)/(mass.pasg/A.pasg) = ',Mass_sum/Area_sum);
      Writeln (outfile9, ' IDEAL mass flow rate / REAL mass flow rate = ',Mass_ratio);
      Writeln ( ' ');
      Writeln ( ' total gap area : ',area_sum:10:5);
      Writeln ( ' Cd= ',Cd:10:6);
      Writeln ( ' IDEAL (mass.gap/A.gap)/(mass.pasg/A.pasg) : ',Mass_sum/Area_sum);
      Writeln ( ' IDEAL mass flow rate / REAL mass flow rate = ',Mass_ratio);
      {-----}

    Close(outfile9);

    Assign (outfile3,outfil3);
    Rewrite (outfile3);
    For J := NX to NP do
      Writeln (outfile3,X[J]);
    Close (outfile3);

    Assign (outfile4,outfil4);
    Rewrite (outfile4);
    For J := NX to NP-1 do
      Writeln (outfile4,Y[J]);
    Close (outfile4);

    Assign (outfile5,outfil5);
    Rewrite (outfile5);
    For J := NX to NP do
      Writeln (outfile5,Velocity[J]);
    Close (outfile5);

    Assign (outfile6,outfil6);
    Rewrite (outfile6);
    For J := NX to NP do
      Writeln (outfile6,-(Flow_angle[J]*DD-(90.0-52.4)));
    Close (outfile6);

    Assign (outfile7,outfil7);
    Rewrite (outfile7);
    For J := NX to NP-1 do
      Writeln (outfile7,P[J]/Cos(Segment_alpha[J]));

```

```
Close (outfile7);
```

```
Assign (outfile8,outfil8);
```

```
Rewrite (outfile8);
```

```
For J := NX to NP-1 do
```

```
  Writeln (outfile8,X2[J]);
```

```
Close (outfile8);
```

```
Assign (outfile10,outfil10);
```

```
Rewrite (outfile10);
```

```
For J := NX to NP-1 do
```

```
  Writeln (outfile10,Area_ary[J]);
```

```
Close (outfile10);
```

```
end.
```

H.2

Program discharge2;

{ MODIFIED SIMPLE MODEL }

(For the contraction pressure difference Rosemount 591 transducer is used while "test section pressure data - inlet static pressure" is measured with Rosemount 633 transducer. If this is not the case modify the transducer calibration factors used in this program (see "const" section))

type

coefmatrix = array[1..200] of real;
array1 = array[1..2,1..40] of real;
array2 = array[1..40] of real;

label step1; label step2;

var

Cntrx, Cntry : array[1..60] of real; { Three-hole probe measurement locations along the blade meanline }

surfxcrdn, surfyocrdn
: array[1..100] of real; { Blade suction surface co-ordinates }

Beta_Normal : array2; { angle of the velocity component normal to the blade centerline relative to the positive side of the x axis.
Determined at each pressure surface tap }

Psurfangle : array2; { Pressure surface angle relative to the positive x direction;
pressure surface tangential velocity will be in this direction }

Flow_Angle : array2; { Resultant flow angle in the gap at a particular pressure surface tap }

surfx, surfy : array2; { Blade suction surface & tip gap stream line cross point co-ordinates }

Dens_Densin : array1; { density/density inlet }

Done, Finished : boolean;

Angle1, Angle2 : real; { Angle1 : Angle of the line that joins the front edge of the centerline segment and the pressure side tap (relative to the positive side of the x axis).
Angle2 is similar for the back edge }

of the centerline segment }

```

Area_ary      : array2;

Normalangle   : real; { angle of the normal vector of the centerline
                        segment relative to the positive side of the x axis }

inp, inq      : real;   { transducer zero readings }
tapx, tapy    : array1; { Blade surface tap co-ordinates }
q, Pin        : array1; { q : Contraction pressure difference }
Ps_Pin, Ps    : array1; { Ps : Static pressure at the blade surface tap }
Pin_Patm      : array1; { For a given contraction pressure difference
                        Pin - Patm is obtained from Pin - Patm vs.
                        contraction pressure difference curve }

VWin          : array1;
I, J, K, n, temporary : integer;
ataprs, DD     : real;
temperature, contrc, tipclr, Real_area : real;
Realmass       : array[1..36] of real;
Ixx, Iyy       : array[1..37] of real;
Rmass_sum      : real;

infile1, infile2, infile3, infile4, infile5, outfile,
infile6, infile7, infile8, infile9, outfile2, outfile3, outfile4, outfile5,
outfile6, outfile7, outfile8, outfile9, outfile10 : text;
infil1, infil2, infil3, infil4, infil5, outfil,
infil6, infil7, infil8, infil9, outfil2, outfil3, outfil4, outfil5,
outfil6, outfil7, outfil8, outfil9, outfil10 : string[25];

Y1, Y2, Y3, Dummy1, Dummy2, Dummy3, m1, m2, c1, c2,
NVelocity, distance1, distance2, P, Cd, XVelocity, YVelocity,
line_slope, constant, PrevAngle, Prevangle1, NVelocity2 : real;
Area, Mass, Mass_sum, Area_sum, Mass_ratio, Mass_real : real;

Velocity      : array2; { Resultant velocity calculated
                        at chordwise stations corresponding
                        to pressure surface tap locations }

V1, V2        : array2; { Velocities normal to the panel formed by
                        points where resultant velocities cross the
                        centerline. }

Segment_alpha : array2; { Angles of this panel relative to the
                        x axis which is tangent to the pressure
                        side of the blade }

X, Y, X2, Y2  : array2; { X,Y co-ordinates of the velocity vector
                        - centerline cross points while X2 is the
                        mid point of these cross points }

NX            : integer;
arrayps       : coefmatrix;
naxps, nps    : integer;

```

```

Answer  : string[25];
NS, NP  : integer;

( NS    : Number of usable taps on the suction surface;
  NP    : Number of usable taps on the pressure surface )

const

    Pcf = 1.373; { calibration factor for transducer used for P-Pa
                  readings (Pa/mv)}
    Qcf = 1.428; { calibration factor for transducer used for
                  contraction pressure difference readings (Pa/mv)}
{-----}

function eval(y : real ; arrayl : coefmatrix ; maxdeg, n : integer ) : real;

{ This function is used to extract the Ps inlet - Pata data from the
  Ps-Pin vs. Psc1-Psc2 calibration curve }

var

    ib, ic, nl2, k, l : integer;
    dk, dkpl, dkp2    : real;

begin { beginning of function eval }

    ib := maxdeg + 1;
    ic := maxdeg + ib - 1;

    { evaluate n = 0, 1 as special cases }

    if (n = 0) then begin
        eval := arrayl[ic];
    end; { of the if statement }

    if (n = 1) then begin
        eval := arrayl[ic] + arrayl[ic+1]*(y-arrayl[1]);
    end; { of the if statement }

    if (n > 1) then begin
        dkp2 := arrayl[ic + n];
        dkpl := arrayl[ic + n - 1] + (y - arrayl[n])*dkp2;
        nl2 := n-2;
        if(nl2 >= 1) then begin
            for l := 1 to nl2 do begin
                k := l+nl2-1;
                dk := arrayl[ic+k] + (y-arrayl[k+1])*dkpl - arrayl[ib+k]*dkp2;
                dkp2 := dkpl;
                dkpl := dk;
            end;
            eval := arrayl[ic] + (y-arrayl[1])*dkpl - arrayl[ib]*dkp2;
        end;
    end;
end;

```

end;

(-----)

begin { beginning of the main program }

temporary := 0;

NS := 32; NP := 30;

DD := 180.0/Pi;

n := NS + NP;

Write (' Enter real mass flow rate ((m/A)/(m.pasg/A.pasg) & . '),

Readln (Mass_real);

Writeln (' ');

Write (' Enter the gap area (m2) corresponding to this mass flow rate : ');

Readln (Real_area);

Writeln (' ');

Write (' Enter the input file name for P-Psin and Psc1-Psc2 values : ');

Readln (infil2);

Writeln (' ');

Write (' Do you want to run the program for row 1 (closest to blade tip) '),

Readln (Answer);

Writeln (' ');

Write (' Enter the output file name for the first part of calculations : ');

Readln (outfil1);

Writeln (' ');

Write (' Enter the output file name for the second part of calculations : ');

Readln (outfil2);

Clrscr;

Writeln (' ');

Write (' Enter output file name for x/c values which will be used for ');

Writeln (' various plots : ');

Readln (outfil3);

Writeln (' ');

Writeln (' Enter output file name for x/c values that will be used for ');

Write (' plotting the mass flow rate and normal vel. distribution : ');

Readln (outfil6);

Writeln (' ');

Write (' Enter output file name for normal vel. values : ');

Readln (outfil4);

Writeln (' ');

Write (' Enter output file name for resultant vel. values : ');

```
Readln (outfil5);
```

```
Writeln (' ');
```

```
Write (' Enter output file name for flow angles : ');
```

```
Readln (outfil6);
```

```
Writeln (' ');
```

```
Write (' Enter output file name for gap mass flow rate distribution : ');
```

```
Readln (outfil7);
```

```
Writeln (' ');
```

```
Writeln (' Enter output file name for panel areas over which linear ');
```

```
Write (' normal velocity distribution will be assumed : ');
```

```
Readln (outfil8);
```

```
Writeln (' ');
```

```
Write (' Enter output file name for detailed mass flow rate calcs. ');
```

```
Readln (outfil9);
```

```
Clrscr;
```

```
Writeln (' ');
```

```
Write (' Enter the tip clearance (t/c) : ');
```

```
Readln (tipclr);
```

```
Clrscr;
```

```
If (Answer = 'N') or (Answer = 'n') then begin
```

```
  Ns := Ns-2; infil1 := 'taps14.dat'; end else infil1 := 'taps1.dat';
```

```
  infil3 := 'array';
```

```
  infil4 := 'centerx';
```

```
  infil5 := 'centery';
```

```
  infil6 := 'prs_tap_ang';
```

```
  infil7 := 'ssrfcrdt';
```

```
  infil8 := 'Mass';
```

```
  infil9 := 'Cntxy';
```

```
( The data from the following two files will be used to correct the real mass  
  flow rate if the ideal flow rate cannot be calculated over the whole chord  
  length )
```

```
Assign (Infile8, infil8);
```

```
Reset (Infile8);
```

```
  For I := 1 TO 36 do
```

```
    Readln (Infile8, Realmass[I]);
```

```
Close (Infile8);
```

```
Assign (Infile9, infil9);
```

```
Reset (Infile9);
```

```
  For I := 1 TO 37 do
```

```
    Readln (Infile9, dummy1, Xxx[I], Yyy[I]);
```

```
Close (Infile9);
```

```
Assign (infil4, infil4);
```

```

Reset (infile4);
  for I := 2 to 52 do
    Readln (infile4,Cntrx[I]);
  Close (infile4);

Clrscr;
Writeln(' Reading the centerline x co-ordinates is completed ');
Writeln(' ');

Assign (infile5,infil5);
Reset (infile5);
  for I := 2 to 52 do
    Readln (infile5,Cntry[I]);
  Close (infile5);

Writeln(' Reading the centerline y co-ordinates is completed ');
Writeln(' ');

      Cntrx[1] := 8.0e-03;
      Cntry[1] := 8.0e-03;
      Cntry[53] := 5.0e-03;
      Cntrx[53] := 1.01;

Assign (infile6,infil6);
Reset (infile6);
  for J := 1 to Np do begin
    Readln (infile6,Psurfangle[J]);
    Psurfangle[J] := -((Psurfangle[J] - (180.0+49.44))*Pi/180.0);
  end;
Close(infile6);

Writeln(' Reading the pressure surface slope is completed ');
Writeln(' ');

Assign (infile7,infil7);
Reset (infile7);
  for I := 1 to 66 do
    Readln (infile7,Dummy1,surfxcrdn[I],surfyocrdn[I]);
    { Starting from the leading edge the "suction" surface co-ordinates are
      read }
  Close (infile7);

Writeln(' Reading the suction surface co-ordinates is completed ');
Writeln(' ');

Assign (infile3,infil3);
Reset (infile3);
  Readln (infile3,maxps,nps);
  for J := 1 to 200 do
    Readln (infile3,arrayps[J]);
  Close (infile3);

Writeln(' Reading the array for the Psin-Pata vs. Psc1-Psc2 least square ');
Writeln(' fitted curve is completed ');

```

```

Writeln(' ');

Assign (infile1,infil1);
Reset (infile1);
{ First the suction surface tap co-ordinates, later the pressure surface
  tap co-ordinates are read ( Pressure surface taps are read from trailing
  edge towards the leading edge ) }

I := 1;
  For J := 1 to Ns do begin
    Readln (infile1,Dummy1, tapx[I,J], tapy[I,J]);
  end;
I := 2;
  For J := 1 to Np do begin
    Readln (infile1,Dummy1, tapx[I,J], tapy[I,J]);
  end;
Close (infile1);

Writeln(' Reading the tap co-ordinates is completed ');
Writeln(' ');

Assign (infile2,infil2);
Reset (infile2);

Readln (infile2,inq); Readln (infile2,inp); Readln (infile2,temperature);
Readln (infile2,atmprs); Readln (infile2,contrc);

{ Atmprs : atmospheric pressure in mmHg
  temperature in 'F
  contrc : contraction factor }
I := 1;
  For J := 1 to Ns do begin
    Readln (infile2,Dummy1,Dummy2,Dummy3,q[I,J],Ps_Pin[I,J]);
  end;
I := 2; J := Np+1;
  While ( J >= 2 ) do begin
    J := J-1;
    Readln (infile2,Dummy1,Dummy2,Dummy3,q[I,J],Ps_Pin[I,J]);
  end;
Close (infile2);

Writeln(' Reading the Psc1-Psc2 and Ps-Pin values is completed ');
Writeln(' ');
Clrscr;

{ Converting atmospheric pressure from mmHg to Pa }

atmprs := (atmprs-0.7)*13.6*9.81*998.6/1000.0;

{ 1- Converting the contraction pressure difference to inlet dynamic
  pressure in Pa:
  2- Converting the P-Psin readings from Volts. to Pa. }

Assign (outfile,outfil);

```

Rewrite (outfile);

```

I := 1,
For J := 1 to Ns do begin
  q[I,J] := (q[I,J]-inq)*Qcf*1000;

  { Using the curve Ps-Patm vs. Psc1-Psc2, calculating the inlet static
    pressure }
  Pin[I,J] := eval( q[I,J],arrayps,maxps,nps) + atmps;

  { Converting Psc1-Psc2 to inlet dynamic pressure using the contraction
    factor }
  q[I,J] := q[I,J]*contrc;

  { Converting the Ps_pin[I,J] reading from Volts to Pa. }
  Ps_Pin[I,J] := (Ps_Pin[I,J]-inp)*Pcf*1000;

  { Calculating the absolute value of the pressure data "Ps" }
  Ps[I,J] := Pin[I,J] + Ps_Pin[I,J];

  { Calculating the density ratio with the assumption that the temperature
    change through the blade row is negligible }
  Dens_Densin[I,J] := Ps[I,J]/Pin[I,J];

  { Calculating the velocity ratio }
  VVin[I,J] := Sqrt( (1.0/Dens_Densin[I,J])*
    ((q[I,J]^2 - Ps_Pin[I,J])/q[I,J]) );

  {-----}
  Writeln (outfile, 'J= ', J:3, ' Suction side VVin = ', VVin[I,J] 10:7);
end;
  Writeln (outfile, ' ');
  {-----}

```

{ Reduction of the data related to the blade pressure surface }

```

I := 2;
For J := 1 to Np do begin
  q[I,J] := (q[I,J]-inq)*Qcf*1000;

  { Using the curve Ps-Patm & Psc1-Psc2 for calculating the inlet static
    pressure }
  Pin[I,J] := eval( q[I,J],arrayps,maxps,nps) + atmps;

  { Converting Psc1-Psc2 into inlet dynamic pressure using the contraction
    factor }
  q[I,J] := q[I,J]*contrc;

  { Converting the Ps_pin[I,J] reading from Volts into Pa. }
  Ps_Pin[I,J] := (Ps_Pin[I,J]-inp)*Pcf*1000;

  { Calculating the absolute value of the pressure data "Ps" }
  Ps[I,J] := Pin[I,J] + Ps_Pin[I,J];

```

```

( Calculating the density ratio with the assumption that the temperature
  change through the blade row is negligible )
  Dens_Densin[I,J] := Ps[I,J]/Pin[I,J];

( Calculating the velocity ratio )
  VVin[I,J] := Sqrt( (1.0/Dens_Densin[I,J])*((q[I,J] - Ps_Pin[I,J])/q[I,J]) );

(-----)
  Writeln (outfile, 'J= ', J:3, ' Pressure side VVin = ', VVin[I,J]:10:7);
end;
  Writeln (outfile, ' ');
(-----)

  Writeln(' VVin values are calculated ');
  Writeln(' ');
  Writeln(' Calculating the normal velocity directions ... ');
  Writeln(' ');

For J := 1 to NP do begin

  If( J = 15) then Clrscr;

  Writeln(' Tap number on the pressure surface : ', J:3);

  Done := false;

  For K := 1 to 52 do begin

    ( Determine the normal velocity direction for each pressure side tap

      First calculating the angle of the lines joining the tap to the
      centerline segment (the angle is calculated relative to the x
      axis where x axis is positive towards the trailing edge and is
      tangent to the pressure side of the blade ) ;
      the front edge of a segment is the one closer to the leading
      edge )

      If ( (Cntrx[K] - Tapx[2,J]) = 0.0 ) then
        Angle1 := Pi/2.0
      else
        Angle1 := Arctan((Cntry[K] - Tapy[2,J])/(Cntrx[K] - Tapx[2,J]));

      If ( (Cntrx[K+1] - Tapx[2,J]) = 0.0 ) then
        Angle2 := Pi/2.0
      else
        Angle2 := Arctan((Cntry[K+1] - Tapy[2,J])/(Cntrx[K+1] - Tapx[2,J]));

      ( Calculating the angle between the normal of the segment and
        the positive side of the x axis )
      If ( (Cntry[K]-Cntry[K+1]) = 0.0 ) then
        Normalangle := Pi/2.0
      else
        Normalangle := Arctan(-(1.0/((Cntry[K] - Cntry[K+1])/
          (Cntrx[K] - Cntrx[K+1]))));

```



```

      If ( Angle1 < 0.0 ) or (( Cntry[K] < Tapy[2,J] ) and
        ( Cntrx[K] < Tapx[2,J] )) then Angle1 := Angle1 + Pi;

      If ( Angle2 < 0.0 ) or (( Cntry[K+1] < Tapy[2,J] ) and
        ( Cntrx[K+1] < Tapx[2,J] )) then Angle2 := Angle2 + Pi;

      If ( Normalangle < 0.0 ) then Normalangle := Pi + Normalangle;

      If (( Normalangle < Angle1 ) and ( Normalangle > Angle2 )) or
        (( Normalangle > Angle1 ) and ( Normalangle < Angle2 )) then begin
{-----}
        Writeln (outfile, ' Normal velocity direction calculation : ');
        Writeln (outfile, ' Velocity vector originating from tap ',J:3);
        Writeln (outfile, ' Pressure surface angle : ',Psurfangle[J]*DD);
        Writeln (outfile, ' Tap co-ordinates : ',Tapx[2,J],', ',Tapy[2,J]);
        Writeln (outfile, ' is normal to centerline segment which is ');
        Writeln (outfile, ' between stations : ',K:3, ' and ',K+1:3);
        Writeln (outfile, ' Station ',K:3, ' coordinates : ',Cntrx[K],', ',Cntry[K]);
        Writeln (outfile, ' Station ',K+1:3, ' coordinates : ',Cntrx[K+1],
          ', ',Cntry[K+1]);
        Writeln (outfile, ' Angle1= ',Angle1*DD:10:7, ' Angle2= ',Angle2*DD:10:7);
        Writeln (outfile, ' Normal angle of this segment : ',Normalangle*DD:10:7);
        Writeln (outfile, ' ');
{-----}

        Beta_normal[J] := Normalangle; Done := true; Goto step1;
      end;

      ( If the point is normal to the center line between two segments : )

      If ( K > 1 ) and
        ( (PrevAngle-Prevangle)*(Normalangle-Angle1) < 0.0 ) then begin
        Writeln ( ' Point is normal to the center line between two segments ');
        Writeln (outfile, ' Point is normal to the center line between two segments ');
        Beta_normal[J] := Angle1; Done := True; Goto step1; end;

        PrevAngle := Normalangle; PrevAngle1 := Angle1;
      end;

      step1:

    end;

  Close(outfile);

  Writeln ( ' Calculation of the normal velocity directions (is completed) ');
  Writeln ( ' ');
  Writeln ( ' Determining the suction surface point where these normal ');
  Writeln ( ' directions originating from pressure side taps meet the suction ');
  Writeln ( ' surface ; Press any key to continue ... ');
  Writeln ( ' ');
  Repeat until KeyPressed ;

```

```

      Clrscr; J := NP+1;

Assign (outfile2,outfil2);
Rewrite (outfile2);

While ( J >= 2 ) do begin
    J := J-1;

    {-----}
    Writeln (outfile2, ' ');
    Writeln (outfile2, ' Tap # : ',J:3);
    Writeln (outfile2, ' Tap co-ordinates ; Tapx/c : ',Tapx[2,J]:10:5, ' Tapy/c : ',
        Tapy[2,J]:10:5);
    {-----}

    If ( Beta_normal[J] <> Pi/2.0 ) then begin
        line_slope := Sin(Beta_normal[J])/Cos(Beta_normal[J]);
        constant := (tapy[2,J]- line_slope*tapx[2,J]); end;

    { Finding the suction surface point which satisfies the equation :
      y = line_slope*x + constant }

    K := 1; Done := False;

    While ( (K <= 65 ) and ( Done = False ) ) do begin

        If ( (surfxcrdn[K]-tapx[2,J]) = 0.0 ) then
            Y1 := Pi/2.0
        else begin
            Y1 := arctan( (surfyocrdn[K]-tapy[2,J])/(surfxcrdn[K]-tapx[2,J]) );
            If ( surfyocrdn[K] < Tapy[2,J] ) and ( surfxcrdn[K] < Tapx[2,J] )
                then Y1 := Y1 + Pi;
        end;

        If ( (surfxcrdn[K+1]-tapx[2,J]) = 0.0 ) then
            Y2 := Pi/2.0
        else begin
            Y2 := arctan( (surfyocrdn[K+1]-tapy[2,J])/(surfxcrdn[K+1]-tapx[2,J]) );
            If ( surfyocrdn[K+1] < Tapy[2,J] ) and ( surfxcrdn[K+1] < Tapx[2,J] )
                then Y2 := Y2 + Pi;
        end;

        If ( Y1 < 0.0 ) then Y1 := Pi + Y1;
        If ( Y2 < 0.0 ) then Y2 := Pi + Y2;
        If ( Beta_normal[J] < 0.0 ) then
            Beta_normal[J] := Pi + Beta_normal[J];

        If ( (Beta_normal[J] < Y1) and (Beta_normal[J] > Y2) ) or
            ( (Beta_normal[J] > Y1) and (Beta_normal[J] < Y2) ) then begin

            { The normal velocity will cross the suction surface edge between
              points K and K+1 ; the equation for this segment of the suction
              surface y = a1*x + c1 }

            {-----}

```

```

Writeln (outfile2, ' Normal velocity direction : ', Beta_normal[J]*DD:10:5);
Writeln (outfile2, ' The normal velocity will cross the suction surface edge of ');
Writeln (outfile2, ' the clearance between surface points K= ', K:3, ' and ',
        K+1:3);
{-----}

Done := True;
m1 := (surfyocrdn[K]-surfyocrdn[K+1])/(surfxocrdn[K]-surfxocrdn[K+1]);
c1 := -surfxocrdn[K]*m1 + surfyocrdn[K];

{ Co-ordinates for the suction surface - flow direction cross point }
If ( Beta_normal[J] <> Pi/2.0 ) then begin
    surfx[J] := (c1-constant)/(line_slope-m1);
    surfy[J] := line_slope*surfx[J] + constant;
end else begin
    surfx[J] := tapx[2,J]; surfy[J] := m1*surfx[J] + c1; end;
end;
K := K+1;
end; { for the while statement }

If ( Done = False ) then begin
{-----}
Writeln (outfile2, ' Normal direction - suction surface meeting point ');
Writeln (outfile2, ' could not be determined');
{-----}

NX := J+1; Goto step2;

end else begin
    NX := 1;
{-----}
Writeln (outfile2, ' Normal flow direction-suction surface cross point ');
Writeln (outfile2, ' X/C = ', surfx[J]:10:5, ' Y/C = ', surfy[J]:10:5);
{-----}
end;

{ Suction surface cross point will be surfx[J] and surfy[J];
now, calculating the static pressure at this point by linear interpolation
between the two taps on both sides of this point }

K := 1; Done := False;
While ( (K <= Ns-1) and ( Done = False )) do begin

    If (( tapx[1,K] < surfx[J] ) and ( tapx[1,K+1] > surfx[J] ))
    or (( tapx[1,K] > surfx[J] ) and ( tapx[1,K+1] < surfx[J] ))
    then begin

        { The cross point is between these two taps ; Interpolating the static
        pressure : }

        distance1 := Sqrt( Sqr(tapx[1,K]-surfx[J]) + Sqr(tapy[1,K]-surfy[J]) );
        distance2 := Sqrt( Sqr(tapx[1,K]-tapx[1,K+1]) +
            Sqr(tapy[1,K]-tapy[1,K+1]) );
    end;
end;

```

```

        P := -( Ps[1,K] - Ps[1,K+1] ) * distance1 / distance2 + Ps[1,K];
        Done := True;
    }-----}
    Writeln (outfile2, ' Point X,Y is between suction surface taps : ',K:3, ' and ',K+1:3);
    Writeln (outfile2, ' And the interpolated static pressure at this point is ');
    Writeln (outfile2, ' Ps (Pa) = ',P:13:8);
    }-----}
    end ;

    If ( surfx[J] < -0.00475 ) then begin
    { point is very close to leading edge; it is between the first
      taps on suction and pressure surface taps; P at this point will be
      approximated to suction surface first tap pressure measurement }

        P := Ps[1,2]; Done := true;
    end;

    K := K + 1;

    end;

    If ( Done = false ) then begin
    }-----}
    Writeln (outfile2, ' The taps on either side of point X,Y could not be ');
    Writeln (outfile2, ' determined; thus interpolation of the ');
    Writeln (outfile2, ' static pressure is not performed for point X,Y ');
    }-----}

    NX := J+1; Goto step2;
    end;

    { Having the static pressure at this point, calculating the normal
      velocity by applying the Bernoulli equation }

    NVelocity := Sqrt( (Ps[2,J]-P)/(dens_densin[2,J]*q[2,J]) );

    { Knowing the normal velocity component, the resultant velocity and flow
      angle can be calculated : }

    Xvelocity := VWin[2,J]*Cos(Psurfangle[J]) + NVelocity*Cos(Beta_Normal[J]);
    Yvelocity := VWin[2,J]*Sin(Psurfangle[J]) + NVelocity*Sin(Beta_Normal[J]);
    Flow_angle[J] := arctan( Yvelocity/Xvelocity );
    Velocity[J] := Sqrt( Sqr(Xvelocity) + Sqr(Yvelocity) );

    }-----}
    Writeln (outfile2, ' NVelocity/Vin = ',NVelocity:10:7);
    Writeln (outfile2, ' Pressure surface angle = ',Psurfangle[J]*DD:10:5);
    Writeln (outfile2, ' Normal velocity direction = ',Beta_Normal[J]*DD:10:5);
    Writeln (outfile2, ' XVelocity/Vin = ',Xvelocity:10:7, ' YVelocity/Vin = ',
        Yvelocity:10:7);
    Writeln (outfile2, ' Flow angle : ',Flow_angle[J]*DD:10:5);
    Writeln (outfile2, ' Resultant Velocity/Vin : ',Velocity[J]:10:7);

```

```

Writeln (outfile2, ' ');
Writeln (outfile2, ' ');
Writeln (outfile2, ' ');
{-----}

end; { For the While j>=2 loop }
      Step2:

      Clrscr;

      Writeln ( ' The velocity magnitude and direction are calculated' );

      { Determining the point where the resultant velocity across the gap
        ( at an angle of Flow_angle[J] and magnitude of Velocity[[J] )
        crosses the centerline : }

      {-----}
      Writeln (outfile2, ' Determining the point where the resultant velocity is ');
      Writeln (outfile2, ' crossing the centerline');
      {-----}

For J := NI to NP do begin

      line_slope := Sin(Flow_Angle[J])/Cos(Flow_Angle[J]);
      Constant := (tapy[2,J] - line_slope*tapx[2,J]);
      { Determining the center line point which satisfies the equation :
        y = line_slope*x + constant }
      {-----}
      Writeln (outfile2, ' Tap # on the pressure surface : ', J-3);
      {-----}

      K := 1; Done := False;
      While ( (K <= 52) and ( Done = False ) ) do begin

            If ( Cntrx[K]-tapx[2,J] = 0.0) then
                  Y1 := Pi/2.0
            else begin
                  Y1 := arctan( (Cntry[K]-tapy[2,J])/(Cntrx[K]-tapx[2,J]) );
                  If ( Cntry[K] < Tapy[2,J] ) and ( Cntrx[K] < Tapx[2,J] )
                        then Y1 := Y1 + Pi;
            end;

            If ( (Cntrx[K+1]-tapx[2,J]) = 0.0) then
                  Y2 := Pi/2.0
            else begin
                  Y2 := arctan( (Cntry[K+1]-tapy[2,J])/(Cntrx[K+1]-tapx[2,J]) );
                  If ( Cntry[K+1] < Tapy[2,J] ) and ( Cntrx[K+1] < Tapx[2,J] )
                        then Y2 := Y2 + Pi;
            end;

            If ( Y1 < 0.0 ) then Y1 := Pi + Y1;
            If ( Y2 < 0.0 ) then Y2 := Pi + Y2;
            If ( Flow_angle[J] < 0.0 ) then

```

```

Flow_angle[J] := Pi + Flow_angle[J];

If ( (Flow_angle[J] < Y1) and (Flow_angle[J] > Y2) ) or
    ( (Flow_angle[J] > Y1) and (Flow_angle[J] < Y2) ) then begin

    { The meeting point will be on segment K which joins the centerline
      stations K and K+1
      Coefficients of the line with "Flow_angle" direction and passing
      through tap [2,J] (pressure side tap J) are line_slope and constant.
      Coefficients for the center line segment are - }

      Done := True;
      m2 := (Cntry[K]-Cntry[K+1])/(Cntrx[K]-Cntrx[K+1]);
      c2 := -Cntrx[K]*m2 + Cntry[K];

      { co-ordinates where these two lines cross each other (ie. the point
        where the normal velocity at tap[2,J] meets the centerline) - }

      X[J] := (c2-constant)/(line_slope-m2);
      Y[J] := line_slope*X[J] + constant;

      end;
      K := K+1;
    end;

    If ( Done = False ) then begin
      {-----}
      Writeln (outfile2, ' Flow direction - center line meeting point ');
      Writeln (outfile2, ' could not be determined');
      {-----}
      temporary := J+1;
    end else begin
      {-----}
      Writeln (outfile2, ' The cross point will be on centerline segment which ');
      Writeln (outfile2, ' joins station : ',K-1:3, ' and ',K:3);
      Writeln (outfile2, ' The cross point co-ordinates/C : ',X[J]:10:5, ' ',Y[J]:10:5);
      Writeln (outfile2, ' ');
      {-----}
    end;

  end;
end; { for the J : for-do loop }

Close (outfile2);

Writeln ( ' Resultant velocity-centerline cross point co-ordinates are calculated' );

Assign (outfile9,outfil9);
Rewrite (outfile9);

If (temporary <> 0) then NX := temporary;

If ( NX > 1 ) Then begin
  Rmass_sun := 0.0; Area_sun := 0.0;
  done := false;
  Writeln ( ' ');

```

```

Writeln ( ' The last velocity vector centerline cross point co-ordinates' );
Writeln ( ' are X = ', X[NX]:10:5, ' Y = ', Y[NX]:10:5 );
For I := 1 to 37 do begin
  If ( done = false ) then begin
    If ( Ixx[I]/250.0 > X[NX] ) then begin
      Writeln ( ' ');
      Writeln ( ' The first centerline station used for THP measurements on ' );
      Writeln ( ' the right side of the above described station is : ',
        Ixx[I]/250.0 );
      Rmass_sum := Rmass_sum + ((Ixx[I]-X[NX]*250.0)/(Ixx[I]-Ixx[I-1]))*
        Realmass[I-1]*Sqrt ( Sqr(Ixx[I]-X[NX]*250.0) +
          Sqr(Yyy[I]-Y[NX]*250.0) )*250.0*tipclr;
      Area_sum := Area_sum + Sqrt ( Sqr(Ixx[I]-X[NX]*250.0) +
        Sqr(Yyy[I]-Y[NX]*250.0) )*250.0*tipclr;
      Writeln ( ' the area between the velocity vector cross location and' );
      Writeln ( ' the first centerline thp measurement point is : ', area_sum:10:5 );
      done := true ;
      For J := I to 36 do begin
        Area := Sqrt ( Sqr(Ixx[J]-Ixx[J+1]) + Sqr(Yyy[J]-Yyy[J+1]) )*250.0*tipclr;
        Rmass_sum := Rmass_sum + Realmass[I]*Area;
        Area_sum := Area_sum + Area;
        Writeln ( ' The total area for which the real mass flow rate will );
        Writeln ( ' not be considered is : ', Area_sum:10:5 );
      end;
    end;
  end;
end;
end;
end;

Mass_real := (Mass_real*Real_area - Rmass_sum)/(Real_area-Area_sum);
Real_area := Real_area - Area_sum;

Area_sum := 0.0; Mass_sum := 0.0;

For J := NX to NP-1 do begin
  Writeln (outfile9, ' X[J] = ', X[J]:10:5, ' Y[J] = ', Y[J]:10:5);
  Writeln (outfile9, ' X[J+1] = ', X[J+1]:10:5, ' Y[J+1] = ', Y[J+1]:10:5);
  Segment_alpha[J] := arctan((Y[J+1]-Y[J])/(X[J+1]-X[J]));
  If (J+1 > Ns) then Dens_Densin[1,J+1] := Dens_Densin[1,J];
  V1[J] := Dens_Densin[1,J]*Velocity[J]*Sin(Flow_angle[J]-Segment_alpha[J]);
  V2[J] := Dens_Densin[1,J+1]*Velocity[J+1]*Sin(Flow_angle[J+1]-
    Segment_alpha[J]);
  Area := Sqrt ( Sqr(X[J]-X[J+1]) + Sqr(Y[J]-Y[J+1]) )*250.0*tipclr*250.0;
  Area_ary[J] := Area;
  F[J] := (V1[J]+V2[J])/2.0;
  Y[J] := (Velocity[J]*Sin(Flow_angle[J]-Segment_alpha[J])+
    Velocity[J+1]*Sin(Flow_angle[J+1]-Segment_alpha[J]))/2.0;
  I2[J] := (X[J] + X[J+1])/2.0;
  Mass := Area*(V1[J]+V2[J])/2.0;
  Mass_sum := Mass_sum + Mass;
  Area_sum := Area_sum + Area;
  Writeln (outfile9, ' J = ', J:3, ' Segment alpha= ', Segment_alpha[J]*DD:10:5,
    ' V1[J]= ', V1[J]:10:5, ' V2[J]= ', V2[J]:10:5);
  Writeln (outfile9, ' Velocity J = ', Velocity[J]:10:5);

```

```

      Writeln (outfile9, ' Velocity J+1 = ', Velocity[J+1]:10:5);
      Writeln (outfile9, ' Area = ', Area:10:5, ' Flow_angle= ', Flow_angle[J]*DD:10:5);
      Writeln (outfile9, ' Mass= ', Mass:10:5);
      Writeln (outfile9, ' X[J]= ', X[J]:10:5, ' Y[J]= ', Y[J]:10:5, ' F[J]= ', F[J]:10:5);
      Writeln (outfile9, ' density[1,J] = ', Dens_Densin[1,J]);
      Writeln (outfile9, ' density[1,J+1] = ', Dens_Densin[1,J+1]);
      Writeln (outfile9, ' ');
      Writeln (outfile9, ' ');
    end;

    Cd := (Mass_real*Real_area)/Mass_sum;

    For J := NX to NP-1 do
      Area_ary[J] := Area_ary[J]/Area_sum;

    (-----)
    Writeln (outfile9, ' ');
    Writeln (outfile9, ' total gap area : ', area_sum:10:5);
    Writeln (outfile9, ' IDEAL (mass.gap/A.gap)/(mass.pasg/A.pasg) : ', Mass_sum/Area_sum);
    Writeln (outfile9, ' REAL mass flow rate /IDEAL mass flow rate (Cd) = ', Cd:10:5);
    Writeln ( ' ');
    Writeln ( ' total gap area : ', area_sum:10:5);
    Writeln ( ' IDEAL (mass.gap/A.gap)/(mass.pasg/A.pasg) : ', Mass_sum/Area_sum);
    Writeln ( ' REAL mass flow rate /IDEAL mass flow rate = ', Cd:10:5);
    (-----)

    Close(outfile9);

    Assign (outfile3,outfil3);
    Rewrite (outfile3);
    For J := NX to NP do
      Writeln (outfile3,X[J]);
    Close (outfile3);

    Assign (outfile4,outfil4);
    Rewrite (outfile4);
    For J := NX to NP-1 do
      Writeln (outfile4,Y[J]);
    Close (outfile4);

    Assign (outfile5,outfil5);
    Rewrite (outfile5);
    For J := NX to NP do
      Writeln (outfile5,Velocity[J]);
    Close (outfile5);

    Assign (outfile6,outfil6);
    Rewrite (outfile6);
    For J := NX to NP do
      Writeln (outfile6,-(Flow_angle[J]*DD-(90.0-52.4)*));
    Close (outfile6);

    Assign (outfile7,outfil7);
    Rewrite (outfile7);

```



```
For J := NX to NP-1 do  
  Writeln (outfile7,Cd*F(J)/Cos(Segment_alpha(J)));  
Close (outfile7);
```

```
Assign (outfile8,outfil8);  
Rewrite (outfile8);  
For J := NX to NP-1 do  
  Writeln (outfile8,X2[J]);  
Close (outfile8);
```

```
Assign (outfile10,outfil10);  
Rewrite (outfile10);  
For J := NX to NP-1 do  
  Writeln (outfile10,Area_ary[J]);  
Close (outfile10);
```

end.

APPENDIX I

Comparison of the Predicted Tip Gap Flow Angle,
Velocity and Mass Flow Rate Distributions With
the Experimental Results ($t/c = 0.02345$ and 0.01981)

Fig. I.1 Tip Clearance Mass Flow Rate Distribution
($Re = 4.3E05$)

Fig. I.2 Tip Clearance Flow Angle Distribution
 $t/c = 0.02845$ $Re = 4.3E05$

Fig. 1.3 Tip Clearance Resultant Velocity Distribution

$t/c = 0.02845$ $Re = 4.3E05$

Fig. I4 Tip Clearance Mass Flow Rate Distribution
 ($Re = 4.3E05$)

Fig. 15 Tip Clearance Flow Angle Distribution
 $t/c = 0.02845$ $Re = 4.3E05$

Fig. 16 Tip Clearance Resultant Velocity Distribution

$t/c = 0.02845$ $Re = 4.3E05$

Fig. I.7 Tip Clearance Mass Flow Rate Distribution
 ($Re = 4.3E05$)

Fig. 1.8 Tip Clearance Flow Angle Distribution

$t/c = 0.04981$ $Re = 4.3E05$

Fig. 1.9 Tip Clearance Resultant Velocity Distribution

$t/c = 0.01981$ $Re = 4.3E05$

Fig. 110 Tip Clearance Mass Flow Rate Distribution
 ($Re = 4.3E05$)

Fig. III Tip Clearance Flow Angle Distribution
 $t/c = 0.01981$ $Re = 4.3E05$

Fig. 112 Tip Clearance Resultant Velocity Distribution
 $t/c = 0.01981$ $Re = 4.3E05$

APPENDIX K**Three-Hole Probe Recalibration Curves**

- Fig. K.1 Variation of $K_{\theta 2}$ With Flow Angle
Fig. K.2 Variation of $K_{\theta 3}$ With Flow Angle
Fig. K.3 Variation of K_{12} With Flow Angle
Fig. K.4 Variation of K_{13} With Flow Angle
Fig. K.5 Variation of K_{23} With Flow Angle
Fig. K.6 Variation of K_1 With Flow Angle

6 of/de 6

0 Low Dynamic Pressure
+ High Dynamic Pressure

Fig. K.1 K_{ϕ_2} VS. FLOW ANGLE

0 Low Dynamic Pressure
+ High Dynamic Pressure

Fig. K.2 K_{03} VS. FLOW ANGLE

0 Low Dynamic Pressure
+ High Dynamic Pressure

Fig. K.3 K_{12} VS. FLOW ANGLE

0 Low Dynamic Pressure
+ High Dynamic Pressure

Fig. K.4 K_{13} VS. FLOW ANGLE

0 Low Dynamic Pressure
+ High Dynamic Pressure

Fig. K.5 K_{22} VS. FLOW ANGLE

o Low Dynamic Pressure
+ High Dynamic Pressure

Fig. K.6 K_1 VS. FLOW ANGLE

APPENDIX L

Blade Surface Static Pressure Distributions
for the Rows That Are Not Given In the Main Text

- Fig. L.1 Blade Surface C_p Distribution
 ($t/c = 0.03175$, Rows 5, 8, 10 and 12)
- Fig. L.2 Blade Surface C_p Distribution
 ($t/c = 0.02345$, Rows 5, 6, 8 and 10)
- Fig. L.3 Blade Surface C_p Distribution
 ($t/c = 0.01981$, Rows 5, 6, 8 and 12)

Fig. L.1 BLADE SURFACE C_p DISTRIBUTION
 ($t/c = 0.03175$ $Re = 4.3E05$)

Fig. 1.2 BLADE SURFACE C_p DISTRIBUTION
 ($t/c = 0.02845$ $Re = 4.3E05$)

Fig. L.3 BLADE SURFACE C_p DISTRIBUTION
($t/c = 0.01981$ $Re = 4.3E05$)

END

22-06-88

FIN