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**MEASUREMENT OF THE INTERACTION BETWEEN TIP
LEAKAGE AND SECONDARY FLOWS IN A
TURBINE CASCADE**

by

John Ka Ki Chan

B. Eng. (Mechanical)

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

MASTER OF ENGINEERING

in Mechanical Engineering

**Ottawa-Carleton Institute for Mechanical
and Aerospace Engineering**

**DEPARTMENT OF
MECHANICAL AND AEROSPACE ENGINEERING
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Secondary Flows in a Turbine Cascade**

submitted by

John K.K. Chan, B. Eng.
in partial fulfilment of the requirements
for the degree of Master of Engineering

Thesis Co-Supervisor

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June, 1993

ABSTRACT

The trends in secondary losses with clearance size and inlet tip-wall boundary layer thickness are examined in a linear turbine cascade. The inlet tip-wall boundary layer is thickened by a sawtooth device inserted upstream of the cascade. For both inlet tip-wall boundary layer thicknesses, the downstream flow field is measured for 0.0, 1.5 and 5.5 percent tip clearance sizes. These measurements are collected with a seven-hole pressure probe 0.475 axial chord downstream of the blades. The results are analyzed in terms of both vorticity and total pressure loss. The former quantity provides insight into several aspects of the downstream flow field, including size and strength of the tip-leakage and the passage vortices in relation to the tip clearance size and the inlet tip-wall boundary layer thickness. Through examination of the downstream vorticity field, the tip-leakage losses and the secondary losses are isolated from the total pressure losses measured downstream of the blades. The secondary loss was found to decrease by as much as 50 percent when tip clearance size increased. The increase in inlet tip-wall boundary layer thickness resulted in a slight increase in secondary loss. The tip-leakage loss was found to be unaffected by the change in inlet tip-wall boundary layer thickness.

The experimental secondary loss data are used in the end-loss model of Yaras (1990), and this model was found to give very good predictions.

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NOMENCLATURE

A	=area
c	=blade chord length
C_D	=discharge coefficient for tip gap
C_L	=lift coefficient
c_x	=blade axial chord length
C_{P0}	=total pressure loss coefficient= $\frac{P_o - P_{o\alpha}}{\frac{1}{2} \rho V_{\alpha}^2}$
C_P	=static pressure coefficient= $\frac{P - P_{\alpha}}{\frac{1}{2} \rho V_{\alpha}^2}$
C_{P0}[*]	=total pressure loss coefficient averaged over reference mass flow rate (Eqn. 5.1.1.1)
h	=span
H	= δ^*/θ =boundary layer shape factor
k_s	=fraction of zero-clearance secondary loss still present with clearance (Section 5.4)
K_E, K_G	=constants related to the blade loading distribution (Section 2.2)
$\dot{m}_{REF}$	=reference mass flow rate for half passage at inlet
P	=static pressure
P_o	=total pressure
s	=blade spacing
S	=streamwise co-ordinate (Figure 5.1.3.1)
u, v, w	=components of velocity in x, y and z direction
u'	=root mean square velocity fluctuation in the x direction
V	=resultant velocity

x,y,z	=co-ordinates in axial, tangential and spanwise direction
x'	=co-ordinate in chordwise direction
y'	=local pitchwise co-ordinate (Figure 5.1.3.1)
Y	=total pressure loss coefficient based on outlet dynamic pressure
α	=pitch flow angle, measured from the axial direction
α_m	=mean flow angle= $\tan^{-1}(0.5(\tan\alpha_1 + \tan\alpha_2))$
δ^*	=boundary displacement thickness
δ_x^*	=axial boundary layer displacement thickness
θ_x	=axial boundary layer momentum thickness
ρ	=density
τ	=tip gap height
ω	=vorticity
ω'	=non-dimensional vorticity

SUBSCRIPTS

CL	=centreline value at inlet
m	=mean
n	=component of vector quantity normal to the area of interest
o	=stagnation (total) quantity
REF	=reference
x,y,z,s	=component in x, y, z and streamwise direction

Chapter 1

INTRODUCTION

One of the major factors that influences the aerodynamic performance of turbomachines is tip-leakage loss. It is the loss associated with the leakage flow through the clearance between the blade tip and the annulus wall. This clearance prevents the rubbing of rotating blades against the casing. In today's turbomachines, high compression ratio is used to increase the overall efficiency. This results in small blade size at the last stages of compressors and the first stages of turbines. Thus, the need to reduce the tip-leakage loss becomes even more crucial as the size of the tip clearance becomes rather large relative to the height of these blades. Throughout the past decade, numerous studies have been undertaken concerning tip-leakage flow. During the same time period significant research on tip leakage has also taken place here at Carleton University.

In this university the tip-leakage flow was first investigated by Amrud (1985) using a linear turbine cascade. He examined the effect of tip-leakage on blade loading and found that the blade loading increases as the tip is

approached. This is caused by the presence of the tip-leakage vortex in the vicinity of the blade suction surface near the tip. Amrud observed that this increase in blade loading is mostly in the axial direction.

Yaras (1987) continued the tip-leakage studies in this university by investigating the flow inside the tip gap. The acceleration of the flow into the gap was found to be governed by the "undisturbed" blade pressure difference rather than the highly distorted pressure field near the blade tip. The flow was observed to have finished its acceleration before it entered the tip gap. Finally, a scheme was proposed to predict the velocity distribution of the gap flow, hence the mass flow rate through the gap.

Yaras (1990) continued his own work to study the downstream flow as the tip-leakage flow merges with the passage flow. Detailed downstream flow measurements were performed in the linear cascade. The effects of relative tip-wall motion on the tip gap flow and the downstream flow field were investigated using a moving belt tip-wall on the linear cascade. Several blade tip treatments were examined in an attempt to reduce the aerodynamic losses associated with the tip-leakage flow. Through the experimental observations for the stationary tip-wall case, an end-loss model was proposed based on the assumption that the leakage kinetic energy carried by the normal component of the gap velocity is eventually lost. The three components of the end-loss are the losses introduced inside the gap, the losses associated with the merging of the tip-leakage with the passage flow and the subsequent diffusion of the tip-leakage vortex downstream of the blade row, and finally the losses associated with the passage vortex. Physically sound mathematical models for the first two end-loss components were derived by Yaras (1990), but the last component remained to be modeled.

The end-loss model proposed by Yaras is attractive as it was developed on the basis of a thorough understanding of the tip-leakage flow field. Thus it is highly desirable to complete this loss model and that is essentially the objective of the present work. Review of relevant literature indicated that correlations for

losses associated with the passage vortex for non-zero tip clearances are lacking which justifies the need for further studies in this area.

Downstream measurements were conducted for three different clearance sizes in the same linear turbine cascade used by Amrud and Yaras. The total pressure losses measured downstream of the blades consist of four components, namely, inlet losses, profile losses, tip-leakage losses and losses associated with the passage vortex (secondary losses). Since the last loss component is the one of interest in this study, it needs to be isolated from the other loss components. This was achieved through the study of the downstream vorticity field, which provided the size, location and strength of the individual vortices in the downstream plane.

In addition to the clearance size, one parameter which is likely to affect the secondary loss is the inlet tip-wall boundary layer thickness. The inlet tip-wall boundary layer of the cascade was artificially thickened and the resulting downstream flow was examined. The extracted secondary losses were compared to the ones obtained with the original inlet boundary layer. The accuracy of the end-loss model of Yaras (1990) was re-examined in light of this more extensive secondary loss data.

Chapter 2

LITERATURE REVIEW

2.1 Review of Tip Clearance Studies

As long as half a century ago, researchers began to investigate the nature of the tip-leakage flow in turbomachines. Through the years many aspects of the flow have been examined experimentally, and numerous mathematical models have been projected to predict this flow. A report by Yaras and Sjolander (1991d) provided an extensive critical review of the tip-leakage literature. The following is a condensed version of the review by Yaras and Sjolander. The tip-leakage literature that has been published within the last two years is also covered. In addition, a short review of secondary flow literature is provided as it is relevant to the current work.

2.1.1 Isolated Airfoil

This is one of four types of test methods used in tip-leakage studies, and it is the simplest configuration. Sugiyama (1971) and Lewis and Yeung (1977) used an airfoil mounted between flat parallel walls with a gap at one end of the airfoil to simulate tip-leakage flow. While idealized, this configuration retains the interaction between the tip-wall boundary layer flow and the tip-leakage flow. Lakshminarayana and Horlock (1962) simulated the tip-leakage flow without the effect of tip-wall boundary layer by using an airfoil with a split at midspan. By symmetry, the desired tip clearance was simulated with a split height twice that of the clearance height. Despite its simplicity, this configuration provided useful insight into the tip-leakage flow.

2.1.2 Rectilinear Cascade

A rectilinear cascade usually consists of five blades or more, simulates the tip-leakage flow with a gap between the blades and one of the endwalls. This configuration has been used by many researchers such as Sjolander and Amrud (1987), Yaras and Sjolander (1987), Yamamoto (1988), Dishart and Moore (1989), and Heyes and Hodson (1992). In some cases the tip-leakage flow has been studied without the tip-wall boundary layer effect by inserting a split twice that of the desired tip clearance height at the midspan of the blades. This configuration was used by Khabbaz and Senoo (1961), Yokoyama (1961), and Lakshminarayana and Horlock (1965).

2.1.3 Cascades with Simulated Endwall Motion

Relative motion of rotor blades in turbomachines can be simulated in cascades by implementing endwall motion. One method used by Dean (1954),

Graham (1986), and Yaras (1990) is to replace the endwall of a rectilinear cascade with a moving belt. Another configuration used by Rehbach (1960) and Morphis and Bindon (1988) consists of a stationary annular blade row with a rotating casing.

2.1.4 Rotating Blade Rows

A rotating blade row is certainly the most realistic configuration for the study of tip-leakage flow. Since mid 1980's, through the use of hot wires, high frequency response miniature pressure transducers, and Laser Doppler Velocimeters, researchers such as Murthy and Lakshminarayana (1986), Lakshminarayana et al. (1987), Inoue and Kuroumaru (1989), and Kingcombe et al. (1990) were able to obtain detailed measurements of the tip-leakage flow within compressor and turbine rotors.

2.2 Tip-Leakage Loss Predictions

Some of the models have been simple empirical correlations while others have attempted to model the physics of the flow. There have been two approaches to model the tip-leakage losses based on physical reasoning: one is based on momentum considerations, the other is based on energy considerations.

The models based on momentum considerations use the theory of induced drag for a finite wing to predict the drag induced on the blade by the tip-leakage vortex. One example is the loss model of Ainley and Mathieson (1951) which is one of the most commonly used models in tip-leakage loss predictions. The model assumes the tip-leakage vortex circulation to be equal to the bound circulation; this was undermined by Yaras (1990) who observed the circulation in the tip-leakage vortex to be substantially less than the bound

circulation. Lakshminarayana and Horlock (1965) modified the Ainley and Mathieson model by simulating the tip-leakage vortex with a Rankine vortex. However this model gave poor agreement with the experimental results even though it is more consistent with the flow physics than the Ainley and Mathieson model. Dunham and Came (1970) modified the Ainley and Mathieson model based on more recent cascade data, but their model overestimated the losses.

The tip-leakage loss model based on energy considerations was originally proposed by Rains (1954), who suggested that the energy associated with the tip-leakage flow rolling up into a vortex cannot be recovered. This assumption was supported by the experimental results of Yaras (1990) and Moore and Tilton (1987). The model of Rains was simplified by Vavra (1960) but Vavra's model underestimated the tip-leakage losses measured by Yaras. Yaras (1990) modified Vavra's model based on experimental observations. The resulting expressions for Y_{tip} and Y_{gap} are as follows:

$$Y_{tip} = K_E \frac{C\tau}{hs} C_D \frac{\cos^2 \alpha_2}{\cos^3 \alpha_m} C_L^{1.5}$$

$$Y_{gap} = (-8.89 \left(\frac{\tau}{C} \right) + 0.55) K_G \frac{C_D \sqrt{C_L}}{\cos \alpha_m} \frac{\tau C}{hs}$$

K_E is a blade loading parameter which equals 1.132 for front- or rear-loaded blades and 1.0 for uniform-loaded blades. C_D is the gap discharge coefficient which is approximately equal to 0.75. K_G is also a blade loading parameter which equals 0.943 for front- and rear-loaded blades and 1.0 for uniform-loaded blades. The loss coefficient Y_{tip} accounts for the losses associated with the merging of the tip-leakage flow with the passage flow and the diffusion of the tip-leakage vortex thereafter. Y_{gap} accounts for the losses occurring inside the

tip gap. Besides Y_{tip} and Y_{gap} , the remaining end-loss component is the secondary loss. This term was not correlated by Yaras due to lack of experimental data. Since the end-loss model proposed by Yaras is one of the few in the literature that is derived in a manner consistent with the flow physics, it is highly desirable to complete the model by evaluating the remaining secondary loss term.

2.3 Review of Secondary Loss Studies

Secondary flows in turbomachines are formed from the endwall boundary layers on the hub and casing. For turbine blades with relatively high turning, secondary losses can account for as much as half of the total pressure losses across the blade row. In view of the significance of secondary losses, many experiments have been undertaken to explore this flow. Figure 2.3.1 shows the endwall flow models suggested by Klein (1966) and Langston et al. (1977) in absence of tip-leakage flow. The figure shows that the endwall boundary layer, affected by the pressure gradient in the passage, rolls up into a vortex called the passage vortex. It is located at the corner of the blade suction surface and the endwall. Furthermore, a horseshoe vortex is generated due to the interaction between the inlet boundary layer and the leading edge of the blade. The pressure side leg of the horseshoe vortex has the same direction of rotation as the passage vortex. Langston et al. (1977) suggested that the two vortices merge together which was later observed by Sieverding and Bosche (1983). The suction side leg of the horseshoe vortex rotates in the opposite direction as the passage vortex and Sjolander (1975) and Langston et al. (1977) suggested that it is located at the corner of the blade suction surface and the endwall (shown as counter vortex in Figure 2.3.1). The above descriptions are for a stationary blade row only. When the tip-leakage flow is

Figure 2.3.1 Endwall flow models by Klein (1966) and Langston et al. (1977). (Reproduced from Yaras and Sjolander (1988))

introduced to the blade row, the flow field inside the blade passage becomes more complicated.

Yamamoto (1988) reviewed some of the recent secondary flow research and summarized the complex three-dimensional rotor blade passage flow in a sketch as shown in Figure 2.3.2. The hub endwall flow structure is basically the same as the endwall flow in the stationary blade row. The flow near the tip-wall is dominated by the tip-leakage vortex and the passage vortex. The tip-leakage vortex is located at the corner of the suction side of the blade and the tip-wall. The passage vortex is pushed away from the tip-wall due to the presence of the tip-leakage vortex.

Many secondary loss correlations have been proposed by various researchers and an extensive, critical review of these correlations was presented by Sieverding (1985). The Ainley and Mathieson (1951) secondary loss model was derived based on several assumptions and a correlation of available experimental data. It was very widely used and it also served as the basis for many succeeding secondary loss models. Dunham (1970) modified the Ainley and Mathieson model by taking into account the effect of inlet endwall boundary layer thickness. He suggested that the secondary loss increases as the inlet boundary layer thickens. Mobarak et al. (1988) observed similar behaviour in their cascade. However, Gregory-Smith et al. (1988) did not observe any relationship between the secondary loss and the inlet boundary layer thickness. Thus it appears that further examination of the effect of inlet boundary layer thickness on secondary loss is necessary.

Besides being a function of the inlet boundary layer thickness, the secondary loss is also very likely a function of tip clearance size. However, all the secondary loss models in the available literature are for zero tip clearance only. Due to the close proximity of the tip-leakage vortex and the passage vortex, the main difficulty in investigating the non-zero clearance secondary loss is in separating the secondary loss from the tip-leakage loss. The present work explores one method to tackle this problem.

Figure 2.3.2 Review of flows in turbine passage.
 (Reproduced from Yamamoto (1988))

Chapter 3

DESCRIPTION OF APPARATUS AND INSTRUMENTATION

3.1 Annular Wind Tunnel

A centrifugal fan driven by a variable speed 40 hp DC motor was used as the wind source of the annular wind tunnel. The fan is capable of delivering a maximum flow rate of 4 kg/s at a total pressure rise of 48 cm of water. A schematic of the wind tunnel arrangement is shown in Figure 3.1.1. With an area ratio of 2.72 and an equivalent cone angle of 14 degrees, a straight diffuser (item 4 in Figure 3.1.1) is used to diffuse the high speed air flow into the settling chamber. At the exit of the diffuser, hexagonal honeycomb with cells of 9.5 mm width and 76 mm depth is used to remove any possible swirl in the flow. After the honeycomb the flow enters the settling chamber, which incorporates three screens to reduce mean flow non-uniformities and large scale turbulence. The flow exits the settling chamber through a contraction and enters a transition section. The transition section is used to join the rectangular

Figure 3.1.1.1 Schematic of the Annular Wind Tunnel
(Tremblay, 1990)

test section inlet and the circular settling chamber outlet with a small amount of diffusion (exit to inlet area ratio of 1.2).

3.2 Test Section

The test section, shown in Figure 3.2.1, is a linear cascade with inside dimensions of 675 mm height and 202.3 mm depth. The main frame of the test section is a 7.9 mm thick steel plate which serves as the hub-wall of a row of five turbine blades. The other walls of the test section are constructed from 12.7 mm thick plexiglass. The transparent quality of plexiglass enables oil and smoke flow visualization. The clearance between the blade tip and the tip-wall can be adjusted by inserting shims between the tip-walls and the side-walls. The tip-clearance size was varied from 0.0 to 5.5 percent of the blade chord.

A column of 9.5 mm diameter holes 225 mm upstream of the leading edge plane are used to blow-off the hub-wall boundary layer. The holes are drilled on the back wall at 30 degree to the flow direction and 13 mm apart (centre to centre).

The cascade blades are enlarged versions of the tip section of a turbine rotor blade of Pratt and Whitney, Canada. Based on the specified operating Reynolds number, a blade chord length of 250mm was chosen. All the blades are made of plexiglass except for the instrumented middle blade, which is made of aluminum. The geometry of the blades can be found in Appendix A.

For the pressure probes to access the blade passages, six 20mm-wide-slots filled with aluminum sliders are located on the hub wall. With the traverse gears mounted on the outside of the hub wall, the probe stem extends through the slots into the cascade test section and allows traverses in both spanwise and lateral directions.

Figure 3.2.1 Schematic of the Cascade Test Section

The periodicity of the flow can be adjusted by means of the two side-flaps and the two tail-flaps. The locations of these flaps are shown in Figure 3.2.1.

3.3 Data Acquisition System

Pressure readings are converted into analog signals by two differential pressure transducers. One is made by Rosemount (Model 831A3) and the other is made by MKS Instruments (Baratron Type 220CD-00100A2BS-SPCAL).

The Rosemount transducer has a pressure sensing range of ± 0.5 psid and a full range output of ± 2.5 volts DC. The Baratron, with a built-in temperature sensing stabilizer, is a new addition to the acquisition system featuring a range of ± 1.0 psid, a full range output of ± 10.0 volts. Both of the transducers were calibrated using inclined manometers. The calibrations were checked periodically and it was found that both transducers are very stable. The calibration curves for the transducers are provided in Appendix C.

The electronic measurement unit recording the transducer analog outputs is manufactured by Sciometric Instruments (Model 81 measurement system). This unit converts the analog signals into digital signals through a 12 bit analog to digital (A/D) converter. The M81 has four gain settings adjustable through software, allowing the resolution to be maximized for a selected range. The converter has a resolution of 0.024 percent of the selected range.

The M81 is controlled by a Serial Interface unit M901, which is also manufactured by Sciometric Instruments. The M901 provides communication between the M81 and an IBM-compatible Personal Computer through an RS232 serial interface. Various subroutines, written in Turbo Pascal, are used to control the communication process between these hardware components.

3.3.1 Data Sampling Procedure

Each test section data is non-dimensionalized by the reference inlet centreline dynamic pressure, which is proportional to the contraction pressure difference of the wind tunnel. With the two available transducers, the Rosemount was used to measure the contraction pressure difference and the Baratron was used to measure the test section data. The test section pressure data is sent to the Baratron transducer through a 48 port Scanivalve. The stepping of the Scanivalve is controlled through the parallel port of a microcomputer. All the pressure signals are transmitted by flexible Tygon pressure tubing. The tubing was inspected regularly to ensure absence of leaks.

After a series of sampling tests using different pressure sources, it was concluded that a sampling time of 30 second is needed to provide long-term-averaged samples.

A summary of the data sampling procedure for a particular pressure source is as follows:

- i) A waiting time is inserted before every sampling so that the pressure stabilizes after the pressure source is changed from one to another through the Scanivalve. A conservative waiting time of 30 second was adopted after a number of sampling tests.
- ii) 10 seconds of sampling is carried out so that a proper gain can be determined for the M81.
- iii) The actual sampling is carried out for 30 seconds.

3.4 Blade Instrumentation

The aluminum centre blade in the cascade is equipped with static pressure taps. There are ten rows of 0.51mm diameter static pressure taps on

the tip-half of the blade span. On each row, thirty-seven and thirty-six pressure taps are present on the pressure and suction surfaces of the blade, respectively. The first row of static pressure taps is located 4mm from the tip of the blade. There is a 5mm spacing between adjacent rows from row 1 to row 6. From row 6 to row 14, rows are spaced 10mm apart. Since there is not enough room within the blade for each tap to have its own tygon tubing, all the adjacent taps in the spanwise direction are connected together through 3.2mm diameter channels drilled inside the blade. As a result, when measuring the static pressures of a particular row of taps, the remaining rows had to be sealed with thin adhesive tapes. Coordinates of the static pressure taps can be found in Appendix B.

3.5 Seven-Hole Pressure Probe

To measure the static and total pressures together with the three velocity components in the complex three-dimensional flow field downstream of the blades, a seven-hole pressure probe was employed in the non-nulling mode. Other measurement methods were also considered such as hot wire anemometry, laser doppler anemometry and five-hole pressure probes. However, hot wire and laser doppler anemometries lack the ability to measure static pressure and the five-hole probe cannot match the large measurable flow angle range of the seven-hole probe. In addition, the seven-hole probe is relatively inexpensive to manufacture and is durable.

3.5.1 Probe Geometry

The seven-hole probe is made of seven stainless steel tubes, each having an outer diameter of 0.64 mm and an inner diameter of 0.33 mm. The tubes are oriented such that six tubes surround a centre tube. This provides an

axisymmetric arrangement of the tubes. The bundle of tubes is located inside of a brass tube with an inside diameter just large enough to fit the bundle. The tip of the probe is machined to a conical shape with a cone angle of 60 degrees. The space between individual tubes within the bundle is filled with solder. Detailed dimensions of the probe are given in Figure 3.5.1.1.

3.5.2 Probe Calibration

The seven-hole probe used in this experiment was calibrated and used by Yaras (1990). The probe was calibrated in the inviscid core of a jet flow. The core velocity was approximately equal to the cascade exit mid-span, mid passage velocity. The probe was calibrated up to 50 degree flow misalignment with its axis, in 5 degree steps. The probe calibration was checked periodically throughout the experiment.

3.5.3 Accuracy of the Seven-Hole Probe Measurements

3.5.3.1 Curve-Fitting Error

The prime source of error is originated from the use of least-square method to curve-fit to the calibration data. Yaras (1990) concluded that the least-square curve-fitted calibration results in an accuracy of ± 1.5 degree for the measured flow angle. The accuracy for the measured local dynamic and total pressures were found to be ± 4 percent of the actual local dynamic pressure.

3.5.3.2 Wall Proximity Effects

When a probe approaches a solid surface, the flow acceleration between the probe and the surface affects the accuracy of the extracted data. Studies

Figure 3.5.1.1 Dimensions of the Seven-hole Pressure Probe
(Yaras, 1990)

by Sitaram et al. (1981), using a 3.2mm diameter five-hole probe, suggested that this effect contributes negligible error when the probe is more than three or four probe diameters off a solid surface. He also observed errors of two percent in measured total pressure and four percent in measured velocity when the five-hole probe was in contact with a solid surface. Since the seven-hole probe used in the cascade experiments is 25 percent smaller in diameter than the five-hole probe used by Sitaram et al., it is conservative to assume that both probes have similar magnitude of wall proximity errors.

3.5.3.3 Effects of Pressure and Velocity Gradients

When taking measurements inside cascades, multi-hole probes are often exposed to complex three-dimensional flow fields containing steep pressure and velocity gradients (e.g. blade wakes, secondary and tip leakage flows). Due to the finite size of the seven-hole probe, the seven probe pressure readings are associated with slightly different physical locations. Furthermore, when a probe is placed in a velocity gradient, the streamlines deflect toward the region of lower velocity causing errors in probe measurements. A review by Yaras(1990) showed that accurate correction methods for these error sources are not available in published literature.

3.5.3.4 Reynolds Number Effects

Sitaram et al. (1981) examined the effect of Reynolds number on their five-hole probe calibration data and observed that the calibration characteristic was relatively insensitive to Reynolds number variations. The same observation was also noted by Yaras (1990) for a seven-hole probe. Thus in the present work, the Reynolds number effects on the seven-hole probe calibration data were assumed to be negligible.

3.5.3.5 Turbulence Effects

Multi-hole probes are usually calibrated in flows with relatively low turbulence intensity. Therefore probe measurements are likely to be less accurate when they are performed in flows with high turbulence intensity. Sitaram et al. (1981) estimated the error in the velocity measured with a five-hole probe to be approximately 0.33 percent when the probe was placed in a flow with ten percent turbulence intensity.

3.6 Traverse Gears for the Seven-Hole Pressure Probe

The seven-hole probe is positioned in spanwise and pitchwise directions by two sets of traverse gears. Each gear consists of a 4 phase stepping motor driving a 1/4-20 threaded rod. The motors are controlled by two motor controllers which in turn are activated by a microcomputer. The traverse gears are capable of positioning the probe with accuracies of $\pm 0.25\text{mm}$ in the spanwise direction and $\pm 0.10\text{mm}$ in the pitchwise direction. The traversing gear, mounted on the back wall of the test section, is shown in Figure 3.6.1.

3.7 Experimental Set-Up

The schematics of the equipment and its interface during seven-hole probe and blade static pressure measurements are shown in Figure 3.7.1 and 3.7.2, respectively.

Figure 3.6.1 Photograph of the Traverse Gears

FIGURE 3.7.1 EXPERIMENTAL SET-UP FOR SEVEN HOLE PROBE MEASUREMENTS

FIGURE 3.7.2 EXPERIMENTAL SET-UP FOR BLADE STATIC PRESSURE MEASUREMENTS

Chapter 4

CASCADE OPERATING CONDITIONS

4.1 Reynolds Number

The tunnel operating point in terms of Reynolds number was 4.3×10^5 ($\pm 0.1 \times 10^5$). This value is based on the blade chord and cascade inlet centreline velocity. However, the temperature varied by as much as 20 degree Fahrenheit during the course of the experiments. In order to maintain the operating Reynolds number, the inlet velocity was adjusted to compensate for variations in density, ensuring that all data were taken at the above noted Reynolds number.

4.2 Turbulence Intensity

The inlet freestream turbulence intensity, u' / V_{cl} , was measured by Yaras (1990) using hot wire anemometry. At the operating Reynolds number,

the inlet centreline velocity was about 30m/sec and the freestream turbulence intensity in the mainstream direction was about 1.5 percent.

4.3 Inlet Flow

The uniformity of the cascade inlet flow was studied through inlet spanwise pitot tube traverses at the seven positions shown in Figure 4.3.1 with a 0.8mm tip outer diameter pitot tube. The traverses extended 70 percent of the span from the tip-wall. The results of the traverses are given in Figure 4.3.2. The figures show that the inlet freestream flow is quite uniform with a slightly higher dynamic pressure toward the bottom of the cascade inlet. Yaras (1990) observed the same trend and suggested that the use of a centrifugal fan in the wind tunnel causes the dynamic pressure at the bottom of the cascade inlet to be relatively high.

4.3.1 Original Inlet Boundary Layer

The cascade inlet velocity distributions were measured 167mm upstream of the blade row for all three tip clearance sizes. As noted in Section 3.2, shims were inserted between the tip-wall and the sidewalls for adjusting the clearance sizes. These shims created a slope on the tip-wall which varied with clearance sizes. Since the slope on the tip-wall affects the amount of diffusion of the flow before entering the cascade, the cascade inlet tip-wall boundary layer thicknesses were different for all three clearance sizes. The cascade inlet velocity distributions for the three clearance sizes are shown in Figures 4.3.1.1 and 4.3.1.2. The integral parameters of the boundary layer were calculated and they are given in Table 4.3.1.1.

Figure 4.3.1 Inlet flow traverse locations (Yaras, 1990)

Figure 4.3.2 Test section inlet velocity distributions

Figure 4.3.1.1 Cascade inlet velocity distribution

Figure 4.3.1.2 Cascade inlet tip-wall boundary layers.

τ/c	0.0	0.015	0.055
τ (mm)	0.0	3.8	13.7
δ^*_x (mm)	2.9	4.6	3.9
θ_x (mm)	2.2	3.3	3.0
H_x	1.3	1.4	1.3

Table 4.3.1.1 Cascade inlet tip-wall boundary layer parameters

4.3.2 Boundary Layer Thickening Tool

In order to increase the thickness of the tip-wall boundary layer, a sawtooth was inserted at the circular inlet of the transition section (item 8 in Figure 3.1.1). Other boundary layer thickening tools, such as wires and cylindrical obstacles were also considered. However, wires could not generate an adequate increase in boundary layer thickness and cylindrical obstacles could not be adapted into the existing wind tunnel without substantial modifications. Furthermore, the sawtooth is inexpensive to manufacture and it is easily installed in the wind tunnel. Various sawtooth prototypes of different size and shape were tested before arriving at the final configuration. The final sawtooth generated a large increase in tip-wall boundary layer thickness while maintaining lateral uniformity.

The sawtooth is 1mm thick and is made of two layers of cardboard reinforced with glue in between the layers. It consists of seven triangular teeth as shown in Figure 4.3.2.1. Dimensions of the teeth are given in Table 4.3.2.1. The sawtooth is placed at the tip-wall side of the circular inlet of the transition section.

After installing the sawtooth, the inlet flow quality was studied at the seven positions shown in Figure 4.3.1. The measured velocity distributions are given in Figure 4.3.2.2. As is evident, the tip-wall boundary layer thickness is considerably larger while the lateral uniformity is maintained.

4.3.3 Thick Inlet Boundary Layer

The cascade inlet velocity distribution with sawtooth, measured 167mm upstream of the blade row, for the three clearance sizes are shown in Figures 4.3.3.1 and 4.3.3.2. The integral parameters of the thickened cascade inlet tip-

Figure 4.3.2.1 Location of sawtooth inside the circular transition section.

Tooth No.	Height (mm)	Base Width (mm)
1	30	50
2	40	50
3	45	50
4	45	50
5	45	50
6	40	50
7	30	50

Table 4.3.2.1 Dimensions of the teeth of the sawtooth

Figure 4.3.2.2 Test section inlet velocity distributions
(Thick tip-wall boundary layer)

Figure 4.3.3.1 Cascade inlet velocity distribution
(Thick tip-wall boundary layer)

Figure 4.3.3.2 Cascade inlet tip-wall boundary layers
(Thick tip-wall boundary layer).

wall boundary layer were calculated and they are tabulated together with the original boundary layer parameters in Table 4.3.3.1.

4.4 Flow Periodicity

Periodicity of the cascade used in this experiment was first studied by Yaras (1987). In the current work, using the same side-flaps and tailboards settings as Yaras, the periodicity of the cascade was examined through three hole probe traverses at midspan downstream of the blades. The pitchwise total pressure distribution at midspan downstream of the blade row is shown in Figure 4.4.1. As is evident from the figure, acceptable periodicity of the flow through the blade passages was established.

τ/c	0.0	0.015	0.055
τ (mm)	0.0	3.8	13.7
δ^*_x (mm)	2.9	4.6	3.9
θ_x (mm)	2.2	3.3	3.0
H_x	1.3	1.4	1.3

Table 4.3.1.1 Cascade inlet tip-wall boundary layer parameters

τ/c	0.0	0.015	0.055
τ (mm)	0.0	3.8	13.7
δ^*_x (mm)	9.3	9.2	11.0
θ_x (mm)	7.7	7.7	8.7
H_x	1.2	1.2	1.3

Table 4.3.3.1 Cascade inlet tip-wall boundary layer parameters
(Thick tip-wall boundary layer)

Figure 4.4.1 Midspan total pressure distribution downstream of the blade row ($\tau/c = 0.0$).

Chapter 5

PRESENTATION AND DISCUSSION OF RESULTS

5.1 Evaluation of Total Pressure Losses

5.1.1 Mass-Averaged Loss Coefficient Definitions

For effective interpretation of the flow physics, the total pressure losses extracted from different measurement planes need to be expressed in mass-averaged form. To be comparable, mass-averaging in each measurement plane should be performed over the same stream tube and the stream tube should be large enough to include the entire flow field of interest.

In this experiment, the two flow structures of interest are the tip-leakage vortex and the passage vortex. To include these two flow fields, the stream tube needs to cover an area of one half span (from the tip-wall) and one pitch. In the following sections all losses are mass-averaged based on the reference mass flow rate ($\dot{m}_{REF}$) corresponding to cascade inlet free stream fluid passing

through this stream tube. As a result, the mass-averaged total pressure loss coefficient can be defined as follows:

$$C_{P_o}'' = \frac{\int_{\Delta z} \int_{\Delta y} C_{P_o}(y, z) \rho V_x dy dz}{\dot{m}_{REF}} \quad 5.1.1.1$$

The downstream mass flow rates measured over an area of one half span and one pitch were found to be 5 to 10 percent less than the reference mass flow rate. Therefore, it was concluded that the downstream measurement plane did not include the complete inlet stream tube. Yaras (1990) suggested that the presence of the tip-leakage vortex diverged some of the free stream fluid from the inlet stream tube away from the downstream measurement plane. Thus, when performing mass-averaging for the downstream plane, loss free fluid was used to top up the mass flow rate until the reference mass flow rate was attained.

The uncertainty in mass-averaged loss coefficients, based on repeatability tests and probe accuracy (Section 3.5.3), is estimated to be ± 0.01 for the inlet plane and ± 0.03 for the downstream plane. The complex high shear flow downstream of the blade row contributed to the higher uncertainty in the downstream results.

5.1.2 Cascade Inlet and Profile Losses

The mass-averaged total pressure loss coefficients measured at the inlet for each clearance size and tip-wall boundary layer thickness are listed in Table 5.1.2.1. Since the tip-wall boundary layer is the only loss source for the outer half of the cascade inlet flow, the loss coefficient increases as the tip-wall

τ/c	0.000		0.015		0.055	
Boundary Layer Thickness	Orig.	Thick	Orig.	Thick	Orig.	Thick
<i>Inlet C_p''</i>	0.0021	-0.0849	-0.0533	-0.0983	-0.0580	-0.0949
<i>Profile C_p''</i>	-0.044	-0.050	-0.041	-0.053	-0.042	-0.047

Table 5.1.2.1 Calculated mass-averaged loss coefficients.

boundary layer thickens. For the zero clearance case with original inlet boundary layer, the mass-averaged loss coefficient turned out to be positive. This peculiar coefficient is a result of the somewhat non-uniform cascade inlet flow. As shown in Chapter 4, some regions at the inlet have slightly higher total pressure than at the centreline. Since all losses are measured relative to the inlet centreline total pressure and the tip-wall boundary is quite thin for the zero clearance case, a positive mass-averaged inlet total pressure loss coefficient is obtained.

The profile losses for each clearance size and boundary layer thickness are shown in Table 5.1.2.1. They are mass-averaged loss coefficients obtained through pitchwise traverse of the passage flow at midspan. The traverse plane was 1.475 axial chord length downstream from the leading edge plane. This measurement plane will be called plane A hereafter.

5.1.3 Downstream Measurements

All the downstream measurements were collected using a seven-hole pressure probe at plane A. The probe traversed on an evenly spaced grid of one passage height and half span width with a spacing of 5 percent blade span between adjacent measurement stations. The location of plane A and the coordinate system are shown in Figure 5.1.3.1. Figures 5.1.3.2 to 5.1.3.4 present the contours of total pressure loss coefficient obtained at plane A for 0, 1.5, and 5.5 percent clearance with both the original tip-wall boundary layer and the thickened one. The figures show that the losses increase as the clearance size increases. This behaviour is expected since the total pressure loss in the passage outlet flow is dominated by the tip-leakage loss. As the tip clearance size increases, the mass flow through the tip gap increases which results in a larger tip-leakage vortex and associated loss. The total pressure loss distribution is similar for the original and the thick inlet tip-wall boundary layer

Figure 5.1.3.1 Downstream traverse plane and cascade coordinate system

Thickened Inlet Boundary Layer

Original Inlet Boundary Layer

Figure 5.1.3.2 Total pressure loss coefficient distribution in plane A for $r/c = 0.0$.

Original Inlet Boundary Layer

Thickened Inlet Boundary Layer

Figure 5.1.3.3 Total pressure loss coefficient distribution in plane A for $r/c = 0.015$.

Original Inlet Boundary Layer

Thickened Inlet Boundary Layer

Figure 5.1.3.4 Total pressure loss coefficient distribution in plane A for $\tau/c = 0.055$.

cases. Thus, it appears that the thickness of the inlet tip-wall boundary layer does not seriously affect the basic structure of the downstream flow.

The mass-averaged total pressure loss coefficients obtained using plane A data are listed in Table 5.1.3.1. These coefficients confirm the above-described trends in losses with increasing clearance size.

5.1.4 Fully Mixed-Out Loss

To determine the additional diffusion losses downstream from Plane A, a mixing calculation through the use of conservation of mass and momentum relations is performed. The choice of control volume that extends the entire passage pitch provides periodic side boundaries. Therefore the mass and momentum flux through these boundaries can be neglected. The flow is assumed to mix-out at constant area to uniform static pressure and streamwise velocity without any cross flow velocity. After a series of manipulations, the mixed-out velocity, static pressure coefficient and total pressure loss coefficient can be expressed as follows:

$$\frac{V_{mixed}}{V_{\alpha}} = \frac{1}{A_{mixed}} \int_{A_{mixed}} \left(\frac{V_A}{V_{\alpha}} dA \right)$$

$$C_{P_{mixed}} = \frac{1}{A_{mixed}} \left(\int_{A_{mixed}} C_P dA - 2 \left(\frac{V_{mixed}}{V_{\alpha}} \right)^2 A_{mixed} + 2 \int_{A_{mixed}} \left(\frac{V_A}{V_{\alpha}} \right)^2 dA \right)$$

$$C_{P_{o, mixed}} = C_{P_{mixed}} + \left(\frac{V_{mixed}}{V_{\alpha}} \right)^2 = 1.0$$

where

$$dA = (dy \cos \alpha) dz$$

τ/c	0.000		0.015		0.055	
Boundary Layer Thickness	Orig.	Thick	Orig.	Thick	Orig.	Thick
<i>Inlet $C_{p,}''$</i>	0.0021	-0.0849	-0.0533	-0.0983	-0.0580	-0.0949
<i>Profile $C_{p,}''$</i>	-0.044	-0.050	-0.041	-0.053	-0.042	-0.047
<i>Plane A $C_{p,}''$</i>	-0.123	-0.220	-0.217	-0.311	-0.371	-0.419

Table 5.1.3.1 Calculated mass-averaged loss coefficients.

A_{mixed} is the area of the exit plane of the control volume perpendicular to the streamwise direction and α is the direction of the midspan flow relative to the x-direction in plane A. The mixed-out losses are calculated using Plane A data and they are listed in Table 5.1.4.1. The results show that the majority of the loss generation occurs before Plane A. This behaviour is also noted by Yaras (1990).

5.2 Evaluating the Loss Components by the Vorticity Fields

The complex three dimensional flow downstream of cascades normally consists of more than one vortex structure located in close proximity of each other. Conventional parameters such as the total pressure loss coefficient cannot provide detailed information about these vortices. To the author's knowledge, Inoue and Kuroamaru (1984) were the first to use vorticity to study the complex flow downstream of an axial compressor rotor. Through the use of vorticity, vortices that have opposite directions of rotation can easily be distinguished from each other.

5.2.1 Vorticity Calculation

Vorticity vector components defined in cartesian co-ordinates are as follows:

$$\begin{aligned}\omega_x &= \frac{\partial w}{\partial y} - \frac{\partial v}{\partial z} \\ \omega_y &= \frac{\partial u}{\partial z} - \frac{\partial w}{\partial x}\end{aligned}\tag{5.2.1.1}$$

τ/c	0.000		0.015		0.055	
Boundary Layer Thickness	Orig.	Thick	Orig.	Thick	Orig.	Thick
<i>Inlet C''_{P_0}</i>	0.0021	-0.0849	-0.0533	-0.0983	-0.0580	-0.0949
<i>Profile C''_{P_0}</i>	-0.044	-0.050	-0.041	-0.053	-0.042	-0.047
<i>Plane A C''_{P_0}</i>	-0.123	-0.220	-0.217	-0.311	-0.371	-0.419
<i>Mixed-Out C''_{P_0}</i>	-0.144	-0.244	-0.247	-0.340	-0.408	-0.450

Table 5.1.4.1 Calculated mass-averaged loss coefficients.

$$\omega_z = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$$

The co-ordinate system and the location of the measurement plane are shown in Figure 5.1.3.1. From equations 5.2.1.1 it is evident that a second measurement plane closely spaced to plane A is required to evaluate the y and z vorticity components. Yaras (1990) proposed a simpler method to obtain the vorticity components by using Euler's equation. For steady, incompressible flow, Euler's equation in the x direction can be written as follows:

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} = -\frac{1}{\rho} \frac{\partial P}{\partial x} \quad (5.2.1.2)$$

By adding extra terms to both sides, equation 5.2.1.2 can be rearranged as:

$$v \frac{\partial v}{\partial x} - v \frac{\partial u}{\partial y} - w \frac{\partial u}{\partial z} + w \frac{\partial w}{\partial x} = \frac{1}{\rho} \frac{\partial P}{\partial x} + u \frac{\partial u}{\partial x} + v \frac{\partial v}{\partial x} + w \frac{\partial w}{\partial x} \quad (5.2.1.3)$$

$$v \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right) - w \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right) = \frac{1}{\rho} \left(\frac{\partial P}{\partial x} + \frac{\rho}{2} \frac{\partial u^2}{\partial x} + \frac{\rho}{2} \frac{\partial v^2}{\partial x} + \frac{\rho}{2} \frac{\partial w^2}{\partial x} \right) \quad (5.2.1.4)$$

Substituting the y and z vorticity components (equations 5.2.1.1) into the left hand side of the above equation and rewriting the right-hand-side in terms of total pressure, equation 5.2.1.4 can be written as:

$$v \omega_z - w \omega_y = \frac{1}{\rho} \frac{\partial P_o}{\partial x} \quad (5.2.1.5)$$

Through similar derivation, Euler's equation in the y and z directions can be expressed as:

$$\begin{aligned}\frac{1}{\rho} \frac{\partial P_o}{\partial y} + u \omega_z - w \omega_x &= 0 \\ \frac{1}{\rho} \frac{\partial P_o}{\partial z} - u \omega_y + v \omega_x &= 0\end{aligned}\quad (5.2.1.6)$$

Equations 5.2.1.6 can be rearranged in terms of y and z vorticity components as:

$$\begin{aligned}\omega_z &= \frac{1}{u} (w \omega_x - \frac{1}{\rho} \frac{\partial P_o}{\partial y}) \\ \omega_y &= \frac{1}{u} (v \omega_x + \frac{1}{\rho} \frac{\partial P_o}{\partial z})\end{aligned}\quad (5.2.1.7)$$

Yaras (1990) verified the applicability of the above equations to the downstream flow. He observed that the vorticity components obtained from two closely spaced measurement planes (using equations 5.2.1.1) were in very good agreement with the vorticity components calculated using equations 5.2.1.7. Thus, for the results presented hereafter, the y and z vorticity components are determined using equations 5.2.1.7.

The vorticity components can be non-dimensionalized as follows:

$$\begin{aligned}\omega'_x &= \frac{\partial(w/V_{cl})}{\partial(y/d)} - \frac{\partial(v/V_{cl})}{\partial(z/d)} \\ \omega'_y &= \frac{1}{u/V_{cl}} \left(\frac{v}{V_{cl}} \omega'_x + \frac{3C_{P_o}}{2\partial(z/d)} \right)\end{aligned}\quad (5.2.1.8)$$

$$\omega'_z = \frac{1}{u/V_{cl}} \left(\frac{w}{V_{cl}} \omega'_x - \frac{\partial C_{p_0}}{2\partial(y/c)} \right)$$

where the velocity components are non-dimensionalized by the cascade inlet centerline velocity, the distances by the length of the blade chord and the total pressure by the inlet centerline dynamic pressure. Through equations 5.2.1.8, it is possible to calculate the three vorticity components by using only plane A measurements. Central differencing is used to evaluate the differential terms in equations 5.2.1.8. At the boundary of the grid, central differencing is not applicable and one-sided differencing is used instead.

After determining the x and y vorticity components, the vorticity field in the streamwise direction is evaluated using the following expression:

$$\omega'_s = \omega'_x \cos \alpha - \omega'_y \sin \alpha \quad (5.2.1.9)$$

The contour plots of the streamwise vorticity for three clearance sizes with the original and the thickened inlet boundary layer are given in Figures 5.2.1.1 to 5.2.1.3.

For zero clearance, the vorticity contours in Figure 5.2.1.1 show that there are two vortices close to the tip-wall. The passage vortex, rotating counter clockwise when viewed from downstream, is the larger of the two vortices. The smaller one rotating in the opposite direction is the suction-side leg of the horseshoe vortex and it is located just above the passage vortex.

For the 1.5 and 5.5 percent clearance cases (Figures 5.2.1.2 and 5.2.1.3), there are also two vortices close to the tip-wall. The dominant one is the tip vortex which rotates in the clockwise direction when viewed from downstream. The other one rotating in the opposite direction is the passage vortex which wraps around the bottom of the tip vortex. For all cases investigated, the size of the passage vortex is quite small due to the relatively low flow turning (about 45 degrees) in the cascade.

Original Inlet Boundary Layer

Thickened Inlet Boundary Layer

Figure 5.2.1.1 Streamwise Vorticity distribution in plane A for $\tau/c = 0.0$.

Original Inlet Boundary Layer

Thickened Inlet Boundary Layer

Figure 5.2.1.2 Streamwise Vorticity distribution in plane A for $r/c = 0.015$.

Original Inlet Boundary Layer

Thickened Inlet Boundary Layer

Figure 5.2.1.3 Streamwise Vorticity distribution in plane A for $\tau/c = 0.055$.

When comparing the tip vortex between the 1.5 and 5.5 percent clearance cases, it appears that as tip-gap size increases, the vortex size increases and the pitch angle of the vortex centerline becomes smaller compared to the exit flow angle at midspan. This trend was also observed by Yaras (1990) who suggested that as the tip-gap size increases, the mass flow rate through the tip-gap increases resulting in a higher momentum normal to the blade chord. The higher mass flow rate through the tip-gap contributes to the increase in tip vortex size, whereas the increase in momentum normal to the blade chord pushes the tip vortex further away from the blade suction surface.

From Figures 5.2.1.1 to 5.2.1.3, it is evident that the thickness of the inlet boundary layer has minimal effect on the location of the vortices. One apparent difference is that the peak values of the streamwise vorticity at the centre of the tip-leakage and passage vortices become smaller as the inlet boundary layer thickens. Gregory-Smith et al. (1988) observed this trend for the secondary flow in their cascade as well. One possible explanation to this behaviour may be the relatively lower blade loading near the blade tip for the thick inlet boundary layer (section 5.3.2). Reduced blade loading implies reduced driving pressure difference for the tip gap flow and reduced blade to blade pressure gradient driving the secondary flow.

5.2.2 Isolating the Loss Components by the Signs of Streamwise Vorticity

The total pressure loss extracted from plane A measurements is composed of the following loss components:

- i) inlet loss;
- ii) profile loss;

- iii) secondary loss;
- iv) tip-leakage loss (for non-zero tip-gap size).

To gain insight into the relative contribution of these loss components, it is necessary to isolate them. The mass-averaged inlet and profile losses for various clearances and inlet boundary layer thicknesses were computed in Section 5.1.2. The net loss (loss generated between the leading edge plane and plane A) can be obtained by subtracting the inlet loss from the mass-averaged loss in plane A. Similarly, the end loss (sum of loss components iii and iv) can be calculated by subtracting the profile loss from the net loss. Secondary loss is associated with the passage vortex and the horseshoe vortex. For zero percent tip clearance, the end loss is the same as the secondary loss since there is no tip-leakage loss. For non-zero tip clearances, the loss associated with the passage vortex is generally classified as secondary loss because the horseshoe vortex is no longer identifiable. A commonly used method to isolate the tip-leakage loss has been to assume that the secondary loss remains constant, regardless the size of the tip gap. In this approach, the tip-leakage loss can be obtained by subtracting the secondary loss for zero clearance from the non-zero clearance end loss. However, the vorticity contour plots in the previous section show that there is a definite change in the size and shape of the passage vortex as clearance size changes. Therefore, the secondary loss is not likely to remain constant as the tip-gap size is varied.

As was noted earlier, the tip-leakage vortex and the passage vortex contain vorticity of opposite signs. Thus the losses associated with these two flow structures may be isolated through the sign of the vorticity field. The tip-leakage vortex has a negative streamwise vorticity whereas the passage vortex has a positive streamwise vorticity. Using the vorticity distribution extracted from plane A measurements, areas of positive vorticity can be separated from

areas of negative vorticity. However, as mentioned earlier in this section, plane measurements contain four loss components. Thus, it is necessary to first remove the inlet and profile losses from the plane A loss data.

The inlet tip-wall boundary layer is the only source of total pressure loss at cascade inlet. However, after the fluid passes through the cascade, it is not possible to identify the portion of the plane A total pressure loss associated with the inlet loss. In absence of an alternative approach, the inlet loss is assumed to be uniformly distributed across the inlet plane. In other words, every unit of mass flow from the inlet plane is assumed to contain the same amount of loss. Thus, according to the distribution of mass flow rate in plane A, the inlet loss can be removed locally from each measurement grid cell.

As mentioned in Section 5.1.2, the profile loss is obtained through pitchwise traverse of the passage at midspan. The profile loss of the entire span is assumed to be the same as that at midspan. Hence, profile loss is easily removed from the overall loss in Plane A.

With the inlet and profile losses removed, the next step is to isolate the tip-leakage and secondary losses. This is done by separating the loss with positive streamwise vorticity from the loss with negative streamwise vorticity. As mentioned in Section 5.1.3, the plane A data were obtained by taking measurements on an evenly spaced grid. Every grid cell consists of four corner nodes and the nodes are the probe measurement stations. If all four corner nodes of a cell are of the same sign of vorticity, then the total pressure loss associated with that cell is accumulated toward the total pressure loss of that particular sign of vorticity. If a cell has three nodes of the same sign of vorticity, then 75 percent of the total pressure loss associated with that cell is accumulated toward the total pressure loss of that particular sign of vorticity. The remaining 25 percent of the total pressure loss is accumulated toward the

total pressure loss of the opposite vorticity sign. For cells that have 2 nodes with positive vorticity and 2 with negative vorticity, the total pressure loss of those cells is divided evenly among the two vorticity signs. The uncertainty of this percentage loss assignment method is estimated to be ± 0.03 by using positive and negative vorticity bias calculations. Positive vorticity bias simply means that as long as there is one or more positive vorticity node in a cell, the total pressure loss associated with that cell is accumulated toward the total pressure loss of positive vorticity. Negative vorticity bias can be explained in the same way. These calculations provide the upper and lower extremes for the losses associated with positive and negative vorticity. The high uncertainty associated with the percentage loss assignment method can be explained by considering the following cases.

From figure 5.2.2.1, case a) shows an example of a grid cell which has two nodes of positive vorticity and two of negative vorticity. Using the percentage loss assignment method, the total pressure loss associated with that cell would be divided evenly toward the total pressure loss associated with positive and negative vorticity. However, from the location of the zero vorticity contour, it is clear that the majority of the total pressure loss is associated with negative vorticity.

Case b) is the opposite of case a) such that the majority of the cell's total pressure loss is associated with positive vorticity.

In case c) the zero vorticity contour splits the cell into two equal halves. However, the steep total pressure loss gradient associated with that cell implies that more total pressure loss should be assigned to positive vorticity than negative vorticity.

Similar cases also occur to cells with three nodes of the same sign of vorticity. In an attempt to reduce the uncertainty, cells that contain both positive

FIGURE 5.2.2.1 Special grid cells with high uncertainty

and negative streamwise vorticity were re-examined individually with reference to the contour plots of the streamwise vorticity and the total pressure loss. For each of these cells, the areas of positive and negative vorticity were identified and the associated total pressure losses were obtained through linear interpolation. This procedure was considerably more time consuming compared to the purely computerized method discussed above. However, the uncertainty in the resultant mass-averaged total pressure loss coefficients should be substantially lower than the uncertainty of ± 0.03 quoted above. The results are tabulated in Table 5.2.2.1.

5.3 Discussion on Loss Variations with Inlet Boundary Layer Thickness and Clearance Size

5.3.1 The Zero Tip Clearance Case

Table 5.2.2.1 shows that for zero tip clearance the secondary loss increases slightly as the inlet tip-wall boundary layer thickness is increased. The breakdown of the loss components in plane A is given in Figure 5.3.1.1.

Many secondary loss related cascade experiments have been performed over the past years. Dunham (1970) reviewed and summarized some of the well known secondary loss correlations at the time. Table 5.3.1.1 gives a comparison between the secondary loss obtained from measurements in the present cascade and the secondary loss values calculated using some of the correlations given by Dunham (1970). A more recent correlation proposed by Kacker and Okapuu (1982) is also included in the comparison. The secondary

τ/c	0.000		0.015		0.055	
Boundary Layer Thickness	Orig.	Thick	Orig.	Thick	Orig.	Thick
<i>Inlet C_{P_o}''</i>	0.0021	-0.085	-0.053	-0.098	-0.058	-0.095
<i>Profile C_{P_o}''</i>	-0.044	-0.050	-0.041	-0.053	-0.042	-0.047
<i>Secondary C_{P_o}''</i>	-0.081	-0.085	-0.033	-0.041	-0.046	-0.066
<i>Tip-Leakage C_{P_o}''</i>	--	--	-0.090	-0.118	-0.225	-0.211

Table 5.2.2.1 Mass-averaged loss coefficients.

Figure 5.3.1.1 Plane A loss distribution at 0% clearance.

	Y _s (zero tip clearance)	
	Original Inlet Boundary Layer	Thick Inlet Boundary Layer
Experimental Results	0.050	0.059
Soderberg, 1949	0.092	0.092
Ehrich, 1954	0.043	0.043
Scholz, 1954	0.085	0.085
Vavra, 1960	0.065	0.065
Boulter, 1962	0.028	0.028
Bauermeister, 1963	0.162	0.162
Dunham, 1970	0.027	0.039
Kacker and Okapuu, 1982	0.068	0.068

Table 5.3.1.1 Experimental and predicted secondary losses.
(Dunham, 1970; Kacker and Okapuu, 1982)

loss coefficient (Y_s) found in Table 5.3.1.1 is commonly used to express total pressure loss and is defined as follows:

$$Y_s = \frac{\text{Stagnation Pressure Loss}}{\text{Outlet Dynamic Head}}$$

The experimental Y_s values given in Table 5.3.1.1 are calculated using the zero clearance mixed-out mass-averaged loss coefficients from Section 5.1.4.

In Table 5.3.1.1, the experimental secondary loss coefficients are within the range of the predicted ones even though they are not in exact agreement with any of the calculated coefficients. Correlations proposed by Vavra and Kacker & Okapuu seem to provide the best predictions.

Dunham's correlation incorporates a correction factor ($f(\delta^+/c)$) which accounts for the change in secondary loss caused by variations in the inlet boundary layer thickness. However, based on examination of overall efficiency data from 25 turbines, Dunham and Came (1970) suggested that the secondary loss is not affected by the inlet boundary layer thickness (i.e. $f(\delta^+/c) = \text{constant}$). Sieverding (1985) reviewed a number of cascade data from different authors and concluded that there exists a critical δ^+/c such that the secondary loss becomes independent of δ^+ when δ^+/c exceeds the critical value. He suggested that the critical δ^+/c is approximately 0.045. Gregory-Smith et al. observed no clear trend of secondary loss with inlet boundary layer thickness. However, all three inlet boundary layer thicknesses that they examined were either close to or above the critical δ^+/c .

In this experiment, both of the inlet boundary layer thicknesses quoted in tables 4.3.1.1 and 4.3.3.1 were below the critical δ^+/c and yet the observed secondary loss increase with increasing boundary layer thickness was quite small. This may imply that the critical δ^+/c quoted by Sieverding is not universal.

5.3.2 The 1.5 Percent Tip Clearance Case

The breakdown of the loss components in plane A for 1.5 percent tip clearance is given in Figure 5.3.2.1. The figure shows that both the secondary loss and tip-leakage loss increase slightly as a result of the increase in inlet boundary layer thickness. The increase in secondary loss is possibly caused by the increase in tip-wall boundary layer fluid associated with the passage vortex as the tip-wall boundary layer thickens.

Oil flow visualizations were performed for both inlet boundary layer thicknesses and the photographs are shown in Figure 5.3.2.2. The only difference between the two photographs is that the separation lines generated by the tip-leakage and passage vortices are slightly closer together for the thick inlet boundary layer case.

The loading distributions of the centre blade were measured for both inlet boundary layer thicknesses and they are shown in Figures 5.3.2.3 to 5.3.2.6. The blade loading distribution for the original inlet boundary layer case is in good agreement with the one observed by Yaras (1987) with a 1.98 percent tip clearance. The trend of the loading distribution is very similar for the two inlet boundary layer thicknesses. The original inlet boundary layer case seems to have a slightly higher blade loading near the tip than the thick inlet boundary layer case. This is expected since the cascade inlet dynamic pressure near the tip region is lower in the thick tip-wall inlet boundary layer case as compared to the original tip-wall inlet boundary layer case.

5.3.3 The 5.5 Percent Tip Clearance Case

The total pressure loss distribution in plane A is given in Figure 5.3.3.1. It is seen that as the inlet boundary layer thickness increases, the secondary loss increased but the tip-leakage loss decreased slightly. The increase in

Figure 5.3.2.1 Plane A loss distribution at 1.5% clearance.

Figure 5.3.2.2 Tip-wall oil flow visualization for $r/c=0.015$
(Top=Original B.L.; Bottom=Thick B.L.).

Figure 5.3.2.3 Blade static pressure distribution for $r/c=0.015$.
(1.98% span from blade tip)

Figure 5.3.2.4 Blade static pressure distribution for $r/c=0.015$.
(4.45% span from blade tip)

Figure 5.3.2.5 Blade static pressure distribution for $r/c=0.015$.
(6.92% span from blade tip)

Figure 5.3.2.6 Blade static pressure distribution for $r/c=0.015$.
(at midspan)

Figure 5.3.3.1 Plane A loss distribution at 5.5% clearance.

secondary loss with increasing inlet boundary layer thickness is in agreement with the other two clearance cases. On the other hand, the decrease in tip-leakage loss as inlet boundary layer thickness is increased is the opposite of the trend in the 1.5 percent clearance case. However, these trends are within the uncertainty range of the data. Thus it appears that there is no clear trend of tip-leakage loss with inlet boundary layer thickness.

Figure 5.3.3.2 shows the photographs of oil flow visualization for both of the inlet boundary layer cases. The oil traces appear to be very similar. Unlike the 1.5 percent tip clearance case, the relative locations of the separation lines generated by the tip-leakage vortex and the passage vortex for both inlet boundary layer thicknesses are almost identical.

Comparison of Figures 5.3.3.2 and 5.3.2.2 shows that for 5.5 percent tip clearance the two separation lines start at about 50 percent axial chord downstream from the leading edge, which is approximately 25 percent axial chord further downstream than the 1.5 percent clearance case. For 5.5 percent tip clearance the separation lines are also further apart as compared to the 1.5 percent clearance case. This is likely caused by the increase in the size of the tip-leakage vortex. Finally, comparison of the locations of the separation lines for the 1.5 and 5.5 percent clearance sizes show that the tip-leakage vortex centreline deviates further from the undisturbed exit flow direction as tip clearance size is increased (as suggested in Section 5.2.1).

5.3.4 Variation of Losses with Clearance Size

From Table 5.2.2.1 it is evident that the tip-leakage loss increases as clearance size is increased. This is caused by the increase in the size of the tip-leakage vortex as tip gap size increases. The effect of inlet boundary layer thickness on tip-leakage loss does not seem to follow a particular trend with clearance size. The observed variations were marginal. The secondary loss

Figure 5.3.3.2 Tip-wall oil flow visualization for $\tau/c=0.055$
(Top=Original B.L.; Bottom=Thick B.L.).

decreases as tip gap size changed from 0 to 1.5 percent but then increases as tip gap size increased from 1.5 to 5.5 percent. The trend is clearly evident in Figure 5.3.4.1. The total pressure loss distributions for different clearance sizes are shown in Figures 5.3.4.2 and 5.3.4.3.

Yaras and Sjolander (1990) suggested that the mixed-out secondary loss should decrease as clearance size increases (as shown in Figure 5.3.4.4). This suggestion was proposed based on the fact that more boundary layer fluid is expected to go through the tip gap and form the tip-leakage vortex as the clearance size is increased. Therefore less boundary layer fluid is expected to become involved in the forming of the passage vortex. The results obtained from the present experiment support the suggestion proposed by Yaras and Sjolander for only part of the clearance size range examined. There does not seem to be an obvious explanation for the observed variation in secondary loss for the 1.5 to 5.5 percent tip clearance size range. However, it is known that the passage vortex forms under the influence of the pitchwise pressure gradient within the passage. The presence of the tip-leakage vortex alters the pressure field considerably. Such an interaction between the passage and tip-leakage vortices may be part of the explanation of the peculiar trend observed.

5.4 Prediction of End Loss

For the tip half of the blade passage, the end loss is defined as:

$$Y_{\text{end}} = Y_{\text{gap}} + Y_{\text{tip}} + k_s Y_{s,0} \quad (5.4.1)$$

where $Y_{s,0}$ is defined as the secondary loss at zero tip clearance. The only unknown term in the above equation is the k_s term. By definition it is the ratio of secondary loss for non-zero and zero tip clearance sizes. In this experiment, the Y_s and $Y_{s,0}$ values were obtained from plane A measurements. In Section 5.1.4 it was shown that majority of the mixing loss occurs upstream of plane A. Therefore it is reasonable to assume that the k_s calculated using plane A data

Figure 5.3.4.1 Plane A secondary loss for various clearances.

Figure 5.3.4.2 Plane A Loss Distribution with original inlet tip-wall boundary layer.

Figure 5.3.4.3 Plane A Loss Distribution with thick inlet tip-wall boundary layer.

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MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No. 2)

Figure 5.3.4.4 Schematic Breakdown of Losses in the End Region Excluding Profile Losses. (Yaras and Sjolander, 1990)

is quite close to the value based on mixed-out secondary losses. The k_s values are plotted in Figure 5.4.1. Clearly k_s is a function of tip gap size and inlet tip-wall boundary layer thickness.

Figure 5.4.2 shows the comparison between various loss models and measurements obtained by Yaras (1990). The $k_s Y_{s,o}$ terms were obtained by multiplying the k_s terms from Figure 5.4.1 with the mixed-out $Y_{s,o}$ calculated using data from Yaras (1990). These secondary loss contributions were then added to the Y_{tip} and Y_{gap} values of Yaras & Sjolander, (1989). The resultant predictions for Y_{end} are compared to the experimental data of Yaras and Sjolander in Figure 5.4.2. From the figure it is evident that the current physically sound model provides one of the most accurate predictions of the experimental end-loss data.

Figure 5.4.1 Plot of k_s as a function of tip clearances.

Figure 5.4.2 Comparison between Tip-Leakage Loss Models and Experimental Results. (Yaras and Sjolander, 1990)

Chapter 6

CONCLUSIONS

The following conclusions can be drawn from the present work.

1. On the current test section set-up, the tip-wall boundary layer thickness was effectively manipulated using a sawtooth device. The desired increase in boundary layer thickness was obtained while maintaining pitchwise uniformity of the incoming flow.
2. Downstream of the cascade the tip-leakage and passage vortices are located in close proximity of each other. Streamwise vorticity was found to be the most effective parameter for discriminating these flow structures. Through the study of the vorticity field it was found that the peak values of the streamwise vorticity at the centre of the tip-leakage and passage vortices become smaller as the inlet tip-wall boundary layer thickens. However, the size, shape and location of the tip-leakage and passage vortices remain quite similar as the inlet tip-wall boundary layer thickens.
3. The total pressure was separately mass averaged over the portions of the downstream plane associated with the passage and tip-leakage vortices. This enabled the evaluation of tip-leakage and secondary loss variations with clearance size and inlet boundary layer thickness.

For all clearance sizes examined, an increase in inlet tip-wall boundary layer thickness resulted in a minor increase in secondary loss. Tip-leakage loss was found to be independent of the inlet tip-wall boundary layer thickness.

The secondary loss decreased as the tip clearance size increased from zero to 1.5 percent. From 1.5 to 5.5 percent tip clearance, the secondary loss increased slightly. The tip-leakage loss continuously increased with increasing clearance size.

4. With the added secondary loss term, the end-loss correlation proposed by Yaras and Sjolander (1989) was found to be in very good agreement with the experimental results.

Chapter 7

RECOMMENDATIONS

The accuracy of the loss components extracted from plane A measurements could be improved by using a finer measurement grid.

One method in estimating the accuracy of the extracted loss components is to re-traverse the complete measurement plane with the identical grid shifted by a half spacing from the original location of the grid. By comparing the loss components obtained by the two grids, the accuracy of the components could be estimated.

Due to the low turning of the blades, the secondary loss in the present cascade is relatively small. In order to generalize findings, more data should be taken using higher turning turbine blades.

More data should be collected to confirm the observed dependence of k_s on the inlet tip-wall boundary layer thickness and clearance size.

REFERENCES

- Amrud, K.K., 1985, "Tip Leakage in a Planar Cascade of Turbine Blades", M.Eng. thesis, Department of Mechanical and Aerospace Engineering, Carleton University, Ottawa, Canada, January 1985.
- Bindon, J.P., 1987, "The Measurement of Tip Clearance Flow Structure on the End-Wall and within the Clearance Gap of an Axial Turbine Cascade", Proc. I.Mech.E., Conference 1986-7, Turbomachinery-Efficiency Prediction and Improvement, September, 1987, pp. 43-52.
- Bindon, J.P. and Morphis, G., 1990, "The Development of Axial Turbine Leakage Loss for Two Profiles Tip Geometries Using Linear Cascade Data", ASME Paper No. 90-GT-152.
- Danias, G., 1987, "Contributions to the Study of Tip Leakage Flow in a Planar Cascade of Turbine Blades", M.Eng. thesis, Carleton University, Department of Mechanical and Aerospace Engineering, Ottawa, Canada, September 1987.
- Dominy, R.G. and Hodson, H.P., 1992, "An Investigation of Factors Influencing the Calibration of 5-Hole Probes for 3-D Flow Measurements", ASME Paper No. 92-GT-216, Presented at the International Gas Turbine and Aeroengine Congress and Exposition, Cologne, Germany, June 1-4, 1992.
- Dunham, J., 1970, "A Review of Cascade Data on Secondary Losses in Turbines", Journal of Mechanical Engineering Science, Vol. 12, No. 1, 1970, pp. 48-59.
- Dunham, J. and Came, P.M., 1970, "Improvements to the Ainley-Mathieson Method of Turbine Performance Prediction", ASME, Journal of Engineering for Power, Vol. 92, No. 3, July 1970, pp. 252-256.
- Gregory-Smith, D.G., Graves, C.P. and Walsh, J.A., 1988, "Growth of Secondary Losses and Vorticity in an Axial Turbine Cascade", ASME Journal of Turbomachinery, Vol. 110, January 1988, pp. 1-8.

Gregory-Smith, D.G., Walsh, J.A., Graves, C.P. and Fulton., K.P., 1988, "Turbulence Measurements and Secondary Flows in a Turbine Rotor Cascade", *Journal of Turbomachinery*, Vol. 110, October 1988, pp. 479-485.

Heyes, F.J.G. and Hodson, H.P., 1992, " The Measurement and Prediction of the Tip Clearance Flow in Linear Turbine Cascade", ASME Paper No. 92-GT-214.

Inoue, M. and Kuroumaru, M., 1984, "Three-Dimensional Structure and Decay of Vortices Behind an Axial Flow Rotating Blade Row", *ASME Journal of Engineering for Gas Turbines and Power*, Vol. 106, July 1984, pp. 561-569.

Inoue, M., Kuroumaru, M. and Fukuhara, M., 1986, "Behavior of Tip Leakage Flow Behind an Axial Compressor Rotor", *ASME Journal of Engineering for Gas Turbines and Power*, Vol. 108, January 1986, pp. 7-14.

Kacker, S.C. and Okapuu, U., 1982, "A Mean Line Prediction Method for Axial Flow Turbine Efficiency", *ASME Journal of Engineering for Power*, Vol.104, January 1982, pp. 111-119.

Kang, S. and Hirsch, C.H., 1992, " Experimental Study on the Three Dimensional Flow within a Compressor Cascade with Tip Clearance: Part I - Velocity and Pressure Fields", ASME Paper No. 92-GT-215.

Kang, S. and Hirsch, C.H., 1992, " Experimental Study on the Three Dimensional Flow within a Compressor Cascade with Tip Clearance: Part II - The Tip Leakage Vortex", ASME Paper No. 92-GT-432.

Kingcombe, R.C., Smith, I.M. and Steeden, R.V., 1990, "Overtip Pressure Measurements in a Cold-Flow Turbine Rig", ASME Paper No. 90-GT-312.

Mobarak, A., Khalafallah, M.G., Osman, A.M. and Heikal, H.A., 1988, "Experimental Investigation of Secondary Flow and Mixing Downstream of Straight Turbine Casades", *ASME Journal of Turbomachinery*, Vol. 110, October 1988, pp. 497-503.

Moore, J. and Adhy, R.Y., "Secondary Flows and Losses Downstream of a Turbine Casade", *ASME Journal of Engineering for Gas Turbines and Power*, Vol. 107, October 1985, pp. 961-968.

Moore, J. and Tilton, J.S., 1987, "Tip Leakage Flow in a Linear Turbine Cascade", ASME Paper No. 87-GT-222.

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.

Sieverding, C.H., 1985a, "Recent Progress in the Understanding of Basic Aspects of Secondary Flows in Turbine Blade Passages", ASME Journal of Engineering for Gas Turbines and Power, Vol. 107, 1985, pp. 248-257.

Sieverding, C.H., 1985b, "Axial Turbine Performance Prediction Methods", Thermodynamic and Fluid Mechanics of Turbomachinery, Vol.2, NATO ASI Series, 1985, pp. 737-784.

Sitaram, N., Lakshminarayana, B. and Ravindranath, A., 1981, "Conventional Probes for the Relative Flow Measurement in a Turbomachinery Rotor Blade Passage", ASME Journal of Engineering for Power, Vol. 103, April 1981, pp. 406-414.

Sjolander, S.A., 1975, "The Endwall Boundary Layer in an Annular Cascade of Turbine Nozzle Guide Vanes", Tech. Rept. ME/A 75-4, Carleton University, 1975.

Sjolander, S.A. and Amrud, K.K., 1987, "Effects of Tip Clearance on Blade Loading in a Planar Cascade of Turbine Blades", ASME Journal of Turbomachinery, Vol. 109, April 1987, pp. 237-245.

Tremblay, B., 1989, "Measurement and Correlation of Off-Design Performance of Axial-Flow Turbines", M.Eng. thesis, Department of Mechanical and Aerospace Engineering, Carleton University, Ottawa, Canada, December 1990.

Walsh, J.A. and Gregory-Smith, D.G., 1987, "The Effect of Inlet Skew on the Secondary Flows and Losses in a Turbine Cascade", I.Mech.E. Paper No. C255/87, 1987, pp. 15-28.

Yamamoto, A., 1988, "Interaction Mechanisms between Tip Leakage Flow and the Passage Vortex in a Linear Turbine Rotor Cascade", ASME Journal of Turbomachinery, Vol. 110, July 1988, pp. 329-338.

Yamamoto, A., 1989, "Endwall Flow/Loss Mechanisms in a Linear Turbine Cascade with Blade Tip Clearance", ASME Journal of Turbomachinery, Vol. 111, July 1989, pp. 264-275.

Yaras, M.I., 1987, "Flow in the Tip Gap of a Rectilinear Turbine Cascade", M.Eng. thesis, Department of Mechanical and Aerospace Engineering, Carleton University, Ottawa, Canada, August 1987.

Yaras, M.I. and Sjolander, S.A., 1989a, "Development of the Tip-Leakage Flow Downstream of a planar Cascade of Turbine Blades: Vorticity Field", ASME Journal of Turbomachinery, Vol. 112, No.4, October 1990, pp. 599-608.

Yaras, M.I. and Sjolander, S.A., 1989b, "Losses in the Tip Leakage Flow of a Planar Cascade of Turbine Blades", AGARD Conference Proceedings No. 469 on Secondary Flows in Turbomachines, Luxembourg, August 1989.

Yaras, M.I., Zhu Y.K., and Sjolander, S.A., 1989, "Flow Fields in the Tip Gap of a Planar Cascade of Turbine Blades", ASME Journal of Turbomachinery, Vol. 111, No. 3, July 1989, pp. 276-283.

Yaras, M.I., 1990, "Measurement and Prediction of Tip-Clearance Effects in a Linear Turbine Cascade", Ph.D thesis, Department of Mechanical and Aerospace Engineering, Carleton University, Ottawa, Canada, December, 1990.

Yaras, M.I. and Sjolander, S.A., 1990, "Prediction of Tip-Leakage Losses in Axial Turbines", ASME Journal of Turbomachinery, Vol.114, No.1, January 1992, pp. 204-210.

Yaras, M.I. and Sjolander, S.A., 1991a, "Effects of Simulated Rotation on Tip Leakage in a Planar Cascade of Turbine Blades Part I: Tip Gap Flow", ASME Journal of Turbomachinery, Vol.114, No.3, July 1992, pp. 652-659.

Yaras, M.I., Sjolander, S.A. and Kind, R.J., 1991b, "Effects of Simulated Rotation on Tip Leakage in a Planar Cascade of Turbine Blades Part II: Downstream Flow Field", ASME Journal of Turbomachinery, Vol.114, No.3, July 1992, pp.660-667.

Yaras, M.I. and Sjolander, S.A., 1991c, "Measurements of the Effects of Winglets on Tip Leakage Losses in a Linear Turbine Cascade", Proceeding of the 10th International Symposium on Air Breathing Engines, Nottingham U.K., September, 1991.

Yaras, M.I. and Sjolander, S.A., 1991d, "Review of Studies on Tip Clearance Effects in Axial Turbomachinery", Report No. M&AE 91-3, Department of Mechanical and Aerospace Engineering, Carleton University, Ottawa, Canada, April 1991.

Appendix A

Geometric specifications of the linear turbine cascade blade:

Nominal blade chord	= 250 mm
Blade height	= 202.3 mm
Blade spacing	= 150 mm
Blade maximum thickness / chord	= 0.0984
Metal turning	= 59.2 deg.
Stagger angle	= 37.6 deg.
Incidence	= -11.1 deg.

Appendix B

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

Tap #	X (inches)	Y (inches)
<hr/>		
(Suction side)		
1	-3.2052	2.8267
2	-2.9803	3.0725
3	-2.7534	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	0.0098
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

Figure B.1 Co-ordinate system for blade static pressure tip locations.
(Yaras, 1990)

Appendix C

Transducer calibration curves

Figure C.1 Rosemount pressure transducer calibration curve.

Figure C.2 Baratron pressure transducer calibration curve.

END

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FIN

hologram, where the shaded regions represent areas having a thickness greater by $\lambda/4$ than that of the unshaded regions. The rings at the outer edge of the hologram are the thinnest and represent the minimum feature size of $\sim 7 \mu\text{m}$ for this hologram.

To measure its characteristics, the Bessel beam HOE was illuminated by a laser diode operating at $\lambda = 830 \text{ nm}$, with a 25.4 mm beamsplitting cube placed between the laser and the hologram. The beam profile was then measured at 2 cm intervals with a CCD camera, beginning at 12 cm from the hologram face. The measured efficiency of the hologram was found to be 33% which comes close to the theoretical maximum of 40.5% for a binary coded phase hologram. The central spot was measured by blocking out the rest of the beam with a pinhole. The central spot was found to contain 9.9% of the total beam energy. A plane mirror was later added to the apparatus to form a variation on the Michelson interferometer in order to examine the phase characteristics of the Bessel beam.

Figure 6-5 illustrates the beam $1/e^2$ intensity radius of the central spot at different points along the optical axis, as well as the $1/e^2$ intensity radius of a Gaussian beam of similar beam waist. The $1/e^2$ intensity radius of the Bessel beam is approximately 100 μm until the beam nears its ray optics maximum propagation distance of 0.78 m. This is the distance where the rays from the outermost regions of the hologram finally intersect, and beyond which none of its rays intersect the optic axis, creating a shadow zone. For comparison, a Gaussian beam with the same spot size has a confocal beam parameter of only 7.57 cm. Figure 6-6 presents the measured as well as predicted axial intensity from a distance of 12 cm from the hologram face up to a distance of 80 cm. The predicted axial intensity was calculated using the Fresnel-Kirchhoff diffraction

Figure 6-5. Measured peak to peak distance from central spot to first ring of the Bessel beam at various distances along the beam's propagation length. The solid line shows the calculated spot size of a Gaussian beam whose beam waist is equal to that of the central peak in the Bessel beam. The measured peak to peak data is also shown at a scale of $\times 10$. The measured data is approximately 1.6 times larger than the $1/e$ amplitude radius for the central peak in the Bessel beam.

Figure 6-6. The data points represent measured intensity of the beam's central spot averaged over five trials. The solid line represents the theoretical axial intensity.

formula in cylindrical coordinates

$$I(\rho) = \left(\frac{\pi}{\lambda z} \right)^2 \left| \int_0^R \exp[ik\sqrt{\rho^2 + \rho'^2 + z_0^2}] J_0(\rho \rho' k/z) \rho' d\rho' \right|^2 \quad (6-26)$$

where ρ is the radial coordinate in the observation plane, ρ' is the radial coordinate in the plane of the hologram, and z_0 is the axial distance from the hologram. The expected linear growth with distance is seen in Figure 6-6 together with an oscillation in the intensity whose amplitude and period increase with distance [6.3, 6.7]. Repeated measurements gave an error bar for the intensity values which for three standard deviations was less than 5%. Figure 6-7 shows photographs of the Bessel beam at a distance of 50 cm from the holographic element. Figure 6-7(a) shows a photograph of the Bessel beam profile with its intense central spot and ~9 outer rings. As mentioned, the Bessel beam has a transverse electric field amplitude which is proportional to the zeroth-order Bessel function of the first kind. The changes in sign of the Bessel function correspond then to borders separating areas of positive electric field amplitude from areas of negative electric field amplitude, and hence these borders separate areas having a phase shift of π radians [6.9]. The borders exist between each of the bright rings, so that each bright ring will be π out of phase with the next. To observe this characteristic, the Michelson interferometer in Figure 6-2 was created. Light from the laser diode is reflected from the plane mirror and forms a plane wave (large radius of curvature) at the observation plane which interferes with the Bessel beam, creating an interference pattern. Moving the plane mirror through a displacement of $\lambda/4$ ($\lambda/2$ optical path length change) shifted the interference pattern, showing that every ring of the Bessel beam is π radians

out of phase with its neighbouring ring. The two photographs of Figures 6-7(c) and 6-7(d) were produced showing, respectively, interference patterns where the odd-numbered rings and the even-numbered rings are suppressed.

Figure 6-7. Photographs of the beam taken at a distance of 50 cm from the hologram face. (a) Photo of the Bessel beam, and (b) an oscilloscope trace of a horizontal section through the center of the ring structure in (a). (c) and (d) are Michelson interferograms of the Bessel beam. With the central spot as the zeroth ring, in (c) the odd numbered rings are suppressed, while (d) shows the even numbered rings suppressed.

Chapter 7

DESIGN AND TEST OF OPTICAL CLOCK DISTRIBUTION SYSTEM

7.1 Optical Beam Routers

If the image stored in a hologram is that of a point source of light, then upon reconstruction with the proper reference beam, the real image of this point source will have a high amount of optical power directed into a relatively small area. The effect is the same as that produced when focussing an optical beam with a convex lens or a concave mirror; for this reason these types of holograms are often called holographic lenses.

Any of the different types of holograms discussed in the previous chapter can be used as beam routers. However some holograms make better beam routers than others. Because their efficiencies are so high, phase holograms are better suited to the job than amplitude holograms. If lenses can be tolerated in the system, Fourier transform holograms can be ideal beam routers. Unfortunately lenses add to the cost and complexity of an optical beam routing system, and take up valuable space as well, so rarely can their use be justified. Although it can be relatively inexpensive to produce one, photographically produced holograms have high unit production costs when high production volumes are desired. Conventional type, computer generated quantized phase holograms possess the most favourable characteristics for beam routers. They are highly efficient, require little space and nothing other than a reference beam to operate, and are easily reproducible on large scales.

When using conventional type phase holograms for beam routers, the simplest HOE (Holographic Optical Element), as mentioned in section 4.2, has zone boundaries identical to those of the Fresnel zone plate. The Fresnel zone plate records the interference pattern produced by a normally incident plane wave and a spherical wave. Using equation (4-11) and setting

$$\begin{aligned} U_r &= U_{or} e^{j\phi_r} \\ U_o &= U_{oo} e^{j\phi_o} \end{aligned} \quad (7-1)$$

we get

$$I = |U_{or}^2 e^{j2\phi_r} + U_{oo}^2 e^{j2\phi_o}| \quad (7-2)$$

By setting $U_{or}=U_{oo}$ and applying a few trigonometric identities, the above expression may be rewritten as

$$I = 2U_{or}(1 + \cos(\phi_r - \phi_o))e^{j(\phi_r + \phi_o)} \quad (7-3)$$

Note that the two phase terms of the interfering waves are subtracted in the amplitude portion of the interference pattern, whereas they are added in the phase portion. By setting $\phi_r=0$ to satisfy the condition of a normally incident plane reference wave, and $\phi_o=k(x^2+y^2+z_o^2)^{1/2}=kr$ for a spherical object wave, we get

$$I = 2U_{or}(1 + \cos(-kr))e^{jkr} \quad (7-4)$$

so the corresponding Fresnel zone plate will have an amplitude variation proportional to $1+\cos(-kr)$ and the corresponding phase-only hologram will have a phase variation $\exp(jkr)$. By quantizing the above expression so that there are only two allowable phase

levels per 2π radians, the result is $kr=n\pi$, where n is the nearest integer. If x^2+y^2 is defined as R^2 on the plane $z=0$, $kr=n\pi$ can be rewritten as

$$R^2 = \left(\frac{n\lambda}{2}\right)^2 - z_o^2 \quad (7-5)$$

which describes the radii of the zones.

7.1.1 Multifacet Holograms

So far only HOEs which produce single spots have been discussed. A multifacet HOE consists of several distinct areas or facets, each of which contain a spot producing hologram. The multifacet HOE is used to direct the light of a source beam into many spot images. Each facet of the hologram focuses light from the reference beam onto a different location, and in doing so provides optical fanout. Figure 7-1 shows a multifacet HOE. The size of each facet is determined by the irradiance distribution function of the reconstructing reference beam and the position of the facet. If equal power output beams are desired, then the powers incident on each facet must be equal. By knowing the irradiance distribution function of the reconstructing beam, and the desired position of the hologram facet, a facet size and shape can be chosen which receives the desired power.

7.2 One to Four Phase Hologram

Two one-to-four phase holograms are produced: one is a binary phase HOE, while the other is a quaternary phase HOE. Each HOE focusses the $0.83 \mu\text{m}$ spherical

Figure 7-1. A multifacet binary amplitude hologram. This hologram produces 4 spots from one input beam.

light wave from a laser diode to the same in line four spot pattern. The theoretical efficiency of the binary phase hologram is 40.5% and that of the quaternary phase HOE is 81%. The phases of each of the input and four output beams can be described as

$$\Phi = \exp(ikr) \quad , \text{where} \quad (7-6)$$

$$r = \sqrt{(x-x_o)^2 + (y-y_o)^2 + (z-z_o)^2}$$

and x_o , y_o , and z_o are different for each beam. According to equation (7-3) the phase of the resulting transmission function is the sum of the object and reference wave phase terms, and so for the binary phase hologram, the locus of points describing the boundaries between half zones is given by

$$\frac{n\lambda}{2} = \sqrt{(x-x_o)^2 + (y-y_o)^2 + (z-z_o)^2} + \sqrt{(x-x_o)^2 + (y-y_o)^2 + (z-z_o)^2} \quad (7-7)$$

where n is an integer. The above equation describes a family of ellipses when n is larger than a critical value. This critical value is the number of half wavelengths in the distance between the input beam source to the centre of the hologram to the focus of the output beam. A similar equation gives the locus of points describing the boundaries separating quarter zones for the quaternary phase hologram.

A computer program written in FORTRAN called TORCH.F was created to generate the masks necessary to produce a multilevel phase hologram of the single facet or multifacet variety. This program is listed in Appendix A.1. It is a user- friendly program which can generate the information necessary to create a focussing hologram given either a collimated or spherical input beam. The program works by solving

equation (7-7) where the phases are computed from information input by the program user. The program computes the data for one quadrant of one facet at a time. The area assigned to each facet is input by the user. The minimum zone number of each hologram is calculated by the computer; the program prompts the user for the size of the minor axis of the elliptical hologram and then computes the maximum zone number and minimum feature size of the mask based on this information. The data the program generates is written to a file in AutoCAD .DXF format so that the mask file may be viewed in AutoCAD before it is fabricated.

The data generated by TORCH.F is used to create an electron beam mask. The e-beam mask generating facility at Northern Telecom has high resolution and is capable of producing step sizes as small as $0.1\mu\text{m}$. The Northern Telecom facility accepts data in GDS2 CAD format, so the .DXF format files generated by TORCH.F must be converted to GDS2 format. One program which performs the necessary conversion is available from Octal Inc. This is the program currently used to convert the files generated by TORCH.F. Any shapes drawn in GDS2 must be closed polygons having no more than 200 vertices. To comply with this limitation, TORCH.F approximates the ellipses it draws with a set of polygons.

The holograms were designed to be placed at a distance of 150 mm away from the diode laser source. The distance of 150 mm was chosen to allow plenty of room for a CCD camera and an optical power meter to have access to the four spots. However, the distance between hologram and laser source could easily be shortened to less than 10 mm in a practical system. The holograms were designed to produce an array of four

spots all in line with the laser diode source. The spot nearest to the laser is 10 mm away, measured in the plane of the laser and detectors, and each successive spot is 8 mm further away. Each hologram facet is a portion of an ellipse as shown in Figure 7-2, and each facet has a surface area of such size that each collects approximately equal optical power. The arrangement illustrated in Figure 7-3 is used to evaluate the HOEs.

The surface area of each facet was determined by integrating the intensity function of the Gaussian beam from the laser diode over a chosen area to determine the optical power falling within that area. This process was repeated until an area for each of the four facets was determined such that each facet received roughly equal optical power. The shape of each facet was determined by a combination of the straight-line boundaries between the facets and the outermost ring of each hologram facet which represents the smallest feature size producible by Carleton's Department of Electronics fabrication facility.

Pulse broadening is an unavoidable characteristic of holographic beam routers. An optical pulse which is focussed by a hologram is broadened in time because of the differential path length available to photons travelling from the laser to the hologram and from there to the detector. A photon which reflects off the innermost ring of the hologram travels a shorter distance from laser to detector than one which is reflected off of the outermost ring. The maximum path difference for the optical arrangement used in this work is 183 μm . This distance corresponds to a delay of 0.61 ps in free

Figure 7-2. Outline of the facets used in both the binary and quaternary phase 1:4 multifacet holograms.

Figure 7-3. Arrangement for testing the 1:4 HOEs. The data collected by the CCD camera is sent to a PC for processing.

space, which can be considered insignificant compared to the pulse period of 1.0 ns.

The clock skew of the system is the time difference between the events of the first and last pulses striking their respective detectors. This time can be calculated using the maximum path difference for the light forming the first and last spots, and the velocity of light in free space. In the case of the system presented, the maximum path difference is 1.59 mm which corresponds to a delay of 5.3 ps. This delay corresponds to 0.5% of the 1.0 ns period of the clock signal. This type of system can have a maximum path difference of up to 150 mm which corresponds to a delay of less than 500 ps between signals.

The holograms were fabricated at Carleton University's Department of electronics fabrication lab by first growing a layer of SiO_2 onto a silicon wafer, a quarter wavelength thick layer for the binary phase hologram and a $3/8$ wavelength thick layer in the case of the quaternary phase hologram. Figure 7-4 illustrates the procedure. Next a layer of photoresist was spun onto the wafer, and the wafer was masked and exposed to UV radiation. The exposed wafer was developed and then bathed in a chemical etchant, eroding away the exposed photoresist. Next, the exposed regions of the SiO_2 layer were etched down to a depth of one quarter wavelength, completing the pattern transfer from the first mask to the wafer. In the case of the quaternary phase hologram the above process, beginning with spinning the wafer with photoresist, must be repeated while using the second mask instead of the first. The final step is to give the hologram a high reflectance by evaporating a layer of aluminum on the wafer. The aluminum layer is 80 nm thick, corresponding to 4.6

Figure 7-4. Lithographic steps in making a quaternary phase hologram.

skin depths in aluminum for radiation of wavelength 0.83 μm . Freshly evaporated aluminum has a maximum normal-incidence reflectance of 86.7% for radiation of 0.83 μm wavelength [7.1] giving a binary phase hologram made with an aluminum coating a maximum efficiency of $0.405 \times 0.867 = 35.1\%$, and a similar quaternary phase hologram a maximum efficiency of $0.81 \times 0.867 = 70.2\%$.

7.3 Electronic Circuitry for Electro-Optic Conversion

In this optical clock distribution system an electrical, sinusoidal clock signal operating at 1 GHz is converted into an optical signal for distribution. At the receiving end of the signal, the optical signal must be converted back to an electrical one in order to communicate with the existing electronics. Optoelectronic components, such as laser diodes and photodiodes, are needed to perform the necessary conversions. Furthermore, additional circuitry is necessary to control the operation of the various optoelectronic components.

The laser diode used in this system is a Sharp model number LT015MD. This laser was chosen because of its high maximum optical output power of 40 mW, and its low attenuation at 1 GHz modulation frequency (<1dB). The Sharp LT015MD operates at a frequency of 830 nm at a case temperature of 25 °C and at 836 nm at a case temperature of 50 °C. Such a wavelength change will cause the photons hitting the outer ring of one of the holograms to be displaced a distance of 75 μm from the focal point at the detector plane. This displacement of photons at the detector plane linearly decreases to zero displacement as the point where the photon strikes the hologram moves inward

toward the center. The effect of a change in wavelength, thus, is a broadening of the focused spot on each of the detectors.

A simple drive circuit was built as shown in Figure 7-5(a) which allowed the laser to be biased in the middle of its output power range at 77.7 mA, while a high frequency sine current wave of amplitude 31.6 mA modulated the laser. The DC biasing circuit has a resistance of 59 Ω including the 3 Ω resistance of the laser diode, and the AC biasing circuit has a resistance of 50 Ω including the resistance of the laser. The AC biasing circuit produces the 31.6 mA current signal from a 1.58 V , 1.0 GHz voltage sine wave and drives the laser from near minimum to maximum forward current when biased at 77.7 mA DC or, equivalently, 4.6 V across the biasing circuit. When the forward current is at its maximum value of 109 mA, the laser's optical power output is 40 mW, and when the forward current is at its minimum value of 46.1 mA the laser output is nearly zero. At maximum power output, roughly 1.46 mW of optical power was measured to strike each facet of the hologram. This small received power is due to the large angular spread of the incident beam together with the long distance from the laser to the hologram. The laser drive circuit is a simple one and contains no automatic power controller, and so the average optical output power will vary with the case temperature of the laser.

At the receiving end of the optical clock signal, an Antel Optronics model FS1002 silicon p-i-n photodiode converts the optical signal into a current signal. It has a responsivity of approximately 0.25 A/W to 830 nm radiation modulated at a frequency of 1 GHz, and its active area has a diameter of 200 μm . Figure 7-5(b)

(a)

(b)

Figure 7-5. (a) Drive circuit for the laser diode and (b) biasing circuit for each of the photodiodes.

illustrates the simple biasing circuit used for the photodiode, which produces a voltage waveform of frequency 1.0 GHz from the current signal produced by the photodiode. The biasing circuit is terminated into the 50 Ω input of either an HP 54120B Digitizing Oscilloscope or an Advantest R3361A spectrum analyzer which are both used to observe the recovered signal.

7.4 Characterization of HOEs

To predict the spot size of each of the hologram faces, a program using the Fresnel-Kirchhoff diffraction integral on a hologram having the outline of a full ellipse of equal major axis to those in the produced hologram was written and executed. The results, as well as the measured spot profiles are displayed in Figures 7-6 and 7-7. The focused spots from the binary hologram are approximately 100 μm in diameter, and are twice as large as the predicted spot size of $\sim 40 \mu\text{m}$. These enlarged spots were the result of charge spillover in a saturated CCD array. Unfortunately, time constraints precluded the option of recollecting spot profile data for the binary hologram, and thus the spot profiles for the binary phase hologram are of limited use, however they are presented nonetheless. The focused spots from the quaternary phase hologram, however, were enlarged five times by a positive lens, so that the image formed on the CCD array was large enough to avoid charge spillover effects. The spot profiles from the quaternary phase hologram were very close in width to that of the predicted profile, as shown in Figure 7-7(b). A comparison of the intensities of the predicted spot profile with those of the measured profiles was not performed

(a)

(b)

Figure 7-6. (a) Relative intensity profiles of the four spots produced by the binary phase HOE. (b) Normalized intensity profiles of first spot, measured and predicted.

(a)

(b)

Figure 7-7. (a) Normalized measured intensity profiles of each of the four spots produced by the quaternary phase hologram. (b) Normalized intensity profiles of the fourth spot, the solid line represents a theoretical profile and the data points represent the measured profile.

because the necessary equipment was not available. The CCD array used to take the spot profile data could give only relative intensity, and was not calibrated to give absolute intensity.

As mentioned previously, the measured maximum power incident upon each facet of the holograms was approximately 1.46 mW. The maximum power measured in each spot produced by the binary phase hologram was roughly 0.51 mW, giving a measured efficiency of 35%, this is close to the maximum efficiency of 35.1% for an aluminum coated binary phase hologram. The measured maximum power in each spot from the quaternary phase hologram was 1.0 mW, corresponding to a measured efficiency of 69% and approaches the maximum efficiency of 70.2% for a quaternary phase hologram with an aluminum coating operating at an 830 nm wavelength.

The maximum power of 0.51 mW produced by each facet of the binary phase hologram is incident on the photodetector in the receiver circuit of Figure 7-5(b), and the detectors responsivity of 0.25 A/W produce a current signal of 0.1275 mA maximum current. The signal is measured across the 50 Ω impedance of the HP digital oscilloscope and so becomes a voltage signal with a theoretical maximum of 6.375 V. Since the laser is biased so that the minimum output power during its 1 ns period is nearly zero, a voltage sine wave of frequency 1 GHz and amplitude 3.19 mV is expected. Figure 7-8a shows a photograph of the actual oscilloscope trace showing a voltage signal of frequency 1 GHz and amplitude 2.4 mV. Likewise, the 1.0 mW maximum optical signal from the quaternary phase hologram will produce, via the receiver circuit, a voltage signal with an ideal maximum of 12.5 mV. Figure 7-8(b)

(a)

(b)

Figure 7-8. Photographs of the oscilloscope traces showing the recovered clock signal using (a) the binary-phase HOE, and (b) the quaternary-phase HOE.

shows the actual oscilloscope trace produced by the optical signal from the quaternary phase hologram; it has an amplitude of approximately 5 mV and a voltage difference between peak and trough of about 10 mV. It is believed that the low experimental voltage readings can be attributed to signal attenuation in the drive circuit for the laser diode and in the biasing circuit for the photodiode. The signal strength compared to the total noise in the system is shown in the spectrum analyzer traces of Figure 7-9. Note that the signal from the binary phase hologram is 21 dB above the noise, while that from the quaternary phase hologram is 28 dB above the noise level.

(a)

(b)

Figure 7-9. Photographs of spectrum analyzer traces showing the strength of the recovered clock signal and the background noise using (a) the binary-phase HOE, and (b) the quaternary-phase HOE.

Chapter 8

CONCLUSIONS AND FUTURE WORK

As a result of the research presented in this thesis, it seems apparent that an optical clock distribution system employing HOEs can effectively route a 1.0 GHz optical clock signal from an optical source to the appropriate detectors. The optical source used was an ordinary diode laser operating at an 0.83 μm wavelength, and the detectors used were simple silicon p-i-n photodiodes. The HOEs used were binary and quaternary, one to four, phase only, reflection holograms. The measured efficiency of the binary and quaternary holograms were 35% and 69% respectively.

The recovered clock signal was converted, optoelectronically by the photodiodes, into an electrical signal without amplifying this signal. It was found that the recovered signal had a SNR of 21 dB in the case of the binary phase HOE, and a SNR of 28 dB for the quaternary phase HOE, indicating that the quaternary phase hologram is roughly twice as efficient as the binary phase type..

The HOEs used to split and route the optical clock signal work by simply focussing the light from the laser diode. Another HOE was also presented which produces a so-called Bessel beam from the laser diode light. Such a beam has a profile which can be described by the zeroth-order Bessel function of the first kind. This Bessel beam has a central spot having a diameter of 200 μm , which is constant $\pm 5\%$ for the beam's propagation distance of 78 cm.

Future work in this area will involve the construction of a clock distribution

system incorporating transmission HOEs etched into a diffractive/reflective substrate [8.1]. Such a method can be more spatially efficient, and could route a signal to a farther lateral destination than can the system presented in this dissertation. An interconnection system using Bessel beams will also be built. One method of using the Bessel beam in an interconnection system involves connecting elements on several daughter cards via an optical backplane. Another involves the use of a Dove prism lying over the circuit board to guide the Bessel beam from the HOE to the detector. Both of these schemes will be considered further.

Recent developments in quantized holography have lead to a new type of binary phase hologram which achieves, theoretically, nearly 100% diffraction efficiency at Bragg incidence [8.2]. This type of hologram has features whose transverse dimension is smaller than the wavelength of the light used on them, and are able to diffract this light at high efficiencies when it satisfies the Bragg condition. Such a design is an alternative approach which avoids the problems of alignment which are inherent in multilevel holograms.

REFERENCES

- [1.1] J. Turunen, J. Fagerholm, A. Vasara, and M.R. Taghizadeh, "Detour-phase kinoform interconnects: the concept and fabrication considerations," *J. Opt. Soc. Am. A* **7**, 1202-1208 (1990).
- [1.2] J.W. Goodman, F.J. Leonberger, S. Kung, and R.A. Athale, "Optical interconnections for VLSI systems," *Proc. of the IEEE* **72**, 850-866, (1984).
- [1.3] D.A.B. Miller, "Optics for low-energy communication inside digital processors: quantum detectors, sources, and modulators as efficient impedance converters," *Opt. Lett.* **14**, 146-148 (1989).
- [2.1] P.R. Haugen, S. Rychnovsky, A. Husain, "Optical interconnects for high speed computing," *Opt. Eng.* **25**, 1076-1084 (1986).
- [2.2] H. Kroger, C. Hilbert, U. Ghoshal, D. Gibson, and L. Smith, "Applications of superconductivity to packaging," *IEEE Circuits and Devices Magazine* **5**, 16-21 (1989).
- [2.3] J.W. Goodman, "Optical interconnections in computing," in *Computation and Cognition. Proceedings of the First NEC Research Symposium*, 22-31 (1991).
- [2.4] N. Streibl, K. Brenner, A. Huang, J. Jahns, J. Jewell, A.W. Lohmann, D.A.B. Miller, M. Murdocca, M.E. Prise, and T. Sizer, "Digital optics," *Proc. of the IEEE* **77**, 1954-1969 (1989).
- [2.5] L.D. Hutcheson, P. Haugen, and A. Husain, "Optical interconnects replace hardwire," *IEEE Spectrum*, 30-35, March 1987.
- [2.6] P.R. Prucnal, "VLSI optical interconnection networks," *SPIE* **703**, Integration and

packaging of optoelectronic devices, 106-115 (1986).

[2.7] J.A. Neff, "Major initiatives for optical computing," *Opt. Eng.* **26**, 2-9 (1987).

[2.8] C.T. Sullivan, "Optical waveguide circuits for printed wire-board interconnections," *SPIE 994 Optoelectronic Materials, Devices, Packaging, and Interconnects II*, 92-100 (1988).

[3.1] H.J. Caulfield, Sun Lu, The Applications of Holography, Wiley-Interscience, Toronto 1970.

[3.2] H.M. Smith, Principles of Holography, Wiley-Interscience, Toronto, 1969.

[3.3] P.W. Milonni, J.H. Eberly, Lasers, Wiley-Interscience, Toronto, 1988.

[3.4] M.V. Klein, T.E. Furtak, Optics, John-Wiley and Sons, Toronto, 1986.

[3.5] E. Hecht, Optics, Second Edition, Addison-Wesley Publishing Co., Reading, Massachusetts, 1987.

[3.6] J.W. Goodman, Introduction to Fourier Optics, McGraw-Hill Book Co., San Francisco, 1968.

[3.7] J.A. Ratcliffe, "Some Aspects of Diffraction Theory and Their Application to the Ionosphere," in A.C. Strickland (ed.), Reports on Progress in Physics, **XIX**, The Physical Society, London, 1956.

[4.1] D. Gabor, "A new microscopic principle," *Nature* **161**, 777 (1948).

[4.2] B.E.A. Saleh, M.C. Teich, Fundamentals of Photonics, Wiley-Interscience, Toronto, 1991.

[4.3] L.B. Lesem, P.M. Hirsch, J.A. Jordan, Jr., "The Kinoform: A new wavefront reconstruction device," *IBM J. Res. Develop.* **13**, 150-155 (1969).

- [4.4] W.H. Lee, "Computer generated Holograms: techniques and applications," *Progress in Optics*, E. Wolf editor, XVI, 119-232 (1978).
- [4.5] J.W. Goodman, A.M. Silvestri, "Some effects of Fourier-domain phase quantization," *IBM J. Res. Develop.* 13, 478-484 (1970).
- [4.6] T.J. McHugh, D.A. Zweig, "Recent Advances in Binary Optics," in Holographic Optics: Optically and Computer Generated, Proc. SPIE 1052, 85-90 (1990).
- [4.7] S. Kirkpatrick, C.D. Gelatt, and M.P. Vecchi, "Optimization by simulated annealing," *Science* 220, 671-680 (1983).
- [5.1] J.A. Cox, T. Werner, J. Lee, S. Nelson, B. Fritz, and J. Bergstrom, "Diffraction efficiency of binary optical elements," SPIE 1211 *Computer and Optically Formed Holographic Optics*, 116-124 (1990).
- [5.2] M.W. Farn, J.W. Goodman, "Effect of vlsi fabrication errors on kinoform efficiency," SPIE 1211 *Computer and Optically Formed Holographic Optics*, 125-136 (1990).
- [6.1] J. Durnin, "Exact solutions for nondiffracting beams. I. The scalar theory," *J. Opt. Soc. Am. A* 4, 651-654 (1987).
- [6.2] J. Durnin, J. J. Miceli Jr., and J. H. Eberly, "Diffraction-free beams," *Phys. Rev. Lett.* 58, 1499-1501 (1987).
- [6.3] J. Turunen, A. Vasara, and A. T. Friberg, "Holographic generation of diffraction-free beams," *Appl. Opt.* 27, 3959-3962 (1988).
- [6.4] R. M. Herman, and T. A. Wiggins, "Production and uses of diffractionless beams," *J. Opt. Soc. Am, A* 8, 932-942 (1991).

- [6.5] L. C. Laycock, and S. C. Webster, "Bessel beams: their generation and application," *GEC J. Research* **10**, 36-51 (1992).
- [6.6] Takehiko Hidaka, "Generation of a diffraction-free laser beam using a specific Fresnel zone plate," *Japanese Journal of Applied Physics* **30**, 1738-1739 (1991).
- [6.7] N. Davidson, A. A. Friesem, and E. Hasman, "Efficient formation of nondiffracting beams with uniform intensity along the propagation direction," *Opt. Commun.* **88**, 326-330 (1992).
- [6.8] A. Vasara, J. Turunen, and A. T. Friberg, "Realization of general nondiffracting beams with computer-generated holograms," *J. Opt. Soc. Am. A* **6**, 1748-1754 (1989).
- [6.9] Y. Lin, W. Seka, J. H. Eberly, H. Huang, and D. L. Brown, "Experimental investigation of Bessel beam characteristics," *Appl. Opt.* **31**, 2708-2713 (1992).
- [6.10] E.T. Whittaker, "On the partial differential equations of mathematical physics," *Math. Ann.* **57**, 333-355 (1902).
- [6.11] F. Gori, G. Guattari, and C. Padovani, "Bessel-Gauss Beams," *Opt. Commun.* **64**, 491-495 (1987).
- [6.12] I.S. Gradshteyn, and Tyzhik, Table of Integrals, Series, and Products, Academic Press, New York, ch. 6 (1980).
- [6.13] R.P. MacDonald, J. Chrostowski, S.A. Boothroyd, and B.A. Syrett, "Holographic formation of a diode laser 'non-diffracting' beam, " *Appl. Opt.*, In Press (1993).
- [6.14] P. L. Overfelt, and C. S. Kenney, "Comparison of the propagation characteristics of Bessel, Bessel-Gauss, and Gaussian beams diffracted by a circular aperture," *J. Opt. Soc. Am. A* **8**, 732-745 (1991).

- [7.1] G. Hass, in R. Kingslake, ed., Applied Optics and Optical Engineering, vol. III, 309-330, Academic Press, New York, 1965.
- [8.1] K.H. Brenner, and F. Sauer, "Diffractive-reflective optical interconnects," *Appl. Opt.* 27, 4251-4254 (1988).
- [8.2] J. Turunen, P. Blair, J. M. Miller, M.R. Taghizadeh, and E. Noponen, "Bragg holograms with binary synthetic surface-relief profile," *Opt. Lett.* 18, 1022-1024 (1993).

Appendix A

Torch.f

```
c Torch.f
c This program computes the equations for a holographic optical
c element and produces the first level mask. A dark field must be
c specified.

c Ryan MacDonald January, 1992

    real cx,pi,min,max,angle,phi,xlo,xhi,ylo,yhi,xo,yo,zo,xi,yi,zi,
+mask,l,m
    open(unit=10,file='holomask.dxf',status='new')

    pi= 3.1415927
c ecc is the eccentricity of the ellipse, that is the major axis
c divided by the minor axis.
    print*, 'Welcome to Torch. Please enter the position, in'
    print*, 'x-y-z coordinates, of the source and detector. The'
    print*, 'hologram will lie in the plane z=0.'
    print*, ''
    print*, 'Enter x coordinate of source'
    read*, xs
    print*, 'Enter y coordinate of source'
    read*, ys
    print*, 'Enter z coordinate of source'
    read*, zo
    print*, 'Would you like to produce a collimated beam (enter 1)
+ or a focused beam (enter 2)?'
    read*, beam
    if (beam.gt. 1.5) then
        print*, 'Enter x coordinate of detector'
        read*, xd
        print*, 'Enter y coordinate of detector'
        read*, yd
```

```

print*, 'Enter z coordinate of detector'
read*, zi
yi= sqrt((xd-xs)**2+(yd-ys)**2)
center=(yi)*zo/(zo+zi)
else
  print*, 'For the collimated beam, enter the refractive index
+ of the medium that the collimated beam will be propagating
+ through.'
  read*, m
  print*, 'Enter the angle, in radians, the beam makes with
+ the x-axis'
  read*, xx
  xd=cos(xx)
  print*, 'Enter the angle, in radians, the beam makes with
+ the y-axis'
  read*, yy
  yd=cos(yy)
  print*, 'Enter the angle, in radians, the beam makes with
+ the z-axis'
  read*, zz
  beta= sqrt(1-(cos(zz))**2)
  print*, 'beta=', beta
  center= zo*tan(asin(m*sin(zz)))
  print*, 'center=', center
endif
print*, 'Please indicate which mask level this mask is for.
+An integer number (1,2,3,...) is required.'
read*, mask
print*, 'Enter the wavelength of light emitted by the source.'
print*, ' '
read*, l

write (10,5) 0
write (10,11) 'SECTION'
write (10,5) 2
write (10,12) 'ENTITIES'
write (10,5) 0

yo= 0.0
print*, 'wavelength=', l

```

- c Calculate minimum number of wavelengths from source to hologram to
c detector.

```

if (beam .gt.1.5) then
min=(sqrt(center**2+zo**2)+sqrt((yi-center)**2+zi**2))/1+.01
c   max= min+3
else
min= (sqrt(center**2+zo**2)-m*beta*(center+yo))/1+.01
endif
print*, 'min=', min
print*, 'distance to hologram center is', center
print*, 'Enter the radius you wish the hologram to have.'
read*, r

c Calculate maximum number of wavelengths from source to hologram to
c detector.
if (beam.gt.1.5) then
max= (sqrt(center**2+r**2+zo**2)+sqrt((yi-center)**2+zi**2+
+ r**2))/1
size= 1/(2*mask*(sin(atan(r/zo))+sin(atan(r/zi))))
if ((xd-xs).GT.-0.00001.AND.(xd-xs).LT.0.00001) then
angle= 0.0
else
if ((xd-xs).GT.0.0) then
angle= atan((yd-ys)/(xd-xs))-pi/2.0
else
angle= atan((yd-ys)/(xd-xs))+pi/2.0
endif
endif
print*, 'angle=', angle
c Angle determines the angle of the y-axis or major axis of
c the ellipse with the y-axis of the coordinate space.
else
max= (sqrt(center**2+r**2+zo**2)-m*beta*(center+yo))/1
c   min=max-5
size= 1/(2*mask*(sin(atan(r/zo))))
if ((xd).GT.-0.00001.AND.(xd).LT.0.00001) then
angle= 0.0
else
if ((xd).GT.0.0) then
angle= atan((yd)/(xd))-pi/2.0
else
angle= atan((yd)/(xd))+pi/2.0
endif
endif
print*, 'angle is=', angle
endif

```

print*, 'The minimum linewidth of this hologram is', size
 print*, 'If this linewidth is too small, use a smaller radius.'

```

c   if ((xd-xs).GT.-0.00001.AND.(xd-xs).LT.0.00001) then
c     angle= 0.0
c   else
c     if ((xd-xs).GT.0.0) then
c       angle= atan((yd-ys)/(xd-xs))-pi/2.0
c     else
c       angle= atan((yd-ys)/(xd-xs))+pi/2.0
c     endif
c   endif
c   print*, 'angle=', angle
c     Angle determines the angle of the y-axis or major axis of
c     the ellipse with the y-axis of the coordinate space.
c   phi= 0.0000001
c     Phi is the starting angle for the calculations.
cx= xs
print*, 'enter the spatial limits of the hologram face'
print*, 'enter the minimum limit in the x-direction'
read*, xlo
print*, 'enter the maximum limit in the x-direction'
read*, xhi
print*, 'enter the minimum limit in the y-direction'
read*, ylo
print*, 'enter the maximum limit in the y-direction'
read*, yhi

print*, 'Calculating hologram mask.'

ticket=1

call polyline(min,max,xs,ys,angle,phi,xlo,xhi,ylo,yhi,mask,
+yi,yo,zi,zo,l,beta,beam,m)

phi=phi + 90
call polyline(min,max,xs,ys,angle,phi,xlo,xhi,ylo,yhi,mask,
+yi,yo,zi,zo,l,beta,beam,m)

phi=phi + 90
call polyline(min,max,xs,ys,angle,phi,xlo,xhi,ylo,yhi,mask,
+yi,yo,zi,zo,l,beta,beam,m)

phi=phi + 90

```

```
call polyline(min,max,xs,ys,angle,phi,xlo,xhi,ylo,yhi,mask,
+yi,yo,zi,zo,l,beta,beam,m)
```

```
print*, 'end'
```

c Now close dxf file

```
write (10,8) 'ENDSEC'
write (10,5) 0
write (10,17) 'EOF'
```

```
5 format (I3)
8 format (A6)
11 format (A7)
12 format (A8)
16 format (A1)
17 format (A3)
end
```

```
*****
```

```
subroutine polyline(min,max,xs,ys,angle,phi,xlo,xhi,ylo,yhi,
+mask,yi,yo,zi,zo,l,beta,beam,m)
```

```
*****
```

c This subroutine computes the vertices of polylines necessary
c to make a hologram, and produces a dxf file containing this
c information.

```
real min,max,xs,ys,cy,angle,theta,rminor,ecc,xi,yi,x,y,n,t,l,
+aa,bb,cc,mask,lest,m
integer tag,ticket,flag
```

```
pi= 3.1415927
```

c Calculate the ring of hologram for each n, where n is the number
c of wavelengths from source to hologram to detector.

```
do 10 n=min,max,1/mask
flag= 0
mark= 1
```

```
do 20 t=0,1
if (beam.gt.1.5) then
```

```

    lest= -(-2*zi**2*zo**2+zi**4+zo**4+yo**4-4*yi**3*yo+
+2*zi**2*yo**2+yi**4+2*yi**2*zo**2+6*yi**2*yo**2-4*yi*yo**3+
+2*yi**2*zi**2-4*yi*zi**2*yo-4*yo*zo**2*yi+2*yo**2*zo**2+
+(n+t/(2*mask))**4*l**4+(-2*yo**2-2*zi**2-2*zo**2-2*yi**2+
+4*yi*yo)*(n+t/(2*mask))**2*l*l)/(-4*(n+t/(2*mask))**2*l*l+
+4*yi**2-8*yi*yo+4*yo**2)
    rminor=sqrt(lest)
    ecc= ((n+t/(2*mask))*l)/sqrt((n+t/(2*mask))**2*l**2+2*yi*yo
+-yi**2-yo**2)
    cy= (-yo*zo**2-yi*zi**2+yi*zo**2+yi*yo**2+zi**2*yo
++yi**2*yo-yi**3-yo**3+(yi+yo)*(n+t/(2*mask))**2*l*l)/
+(2*((n+t/(2*mask))**2*l*l+2*yi*yo-yi**2-yo**2))
    else
        lest= (2*yo*(n+t/(2*mask))*l*m*beta-zo**2+(n+t/(2*mask))
+**2*l**2+m**2*beta**2*yo**2+m**2*beta**2*zo**2)
+/(1-m**2*beta**2)
        rminor=sqrt(lest)
        ecc= 1/(sqrt(1-m**2*beta**2))
        cy= ((n+t/(2*mask))*l*m*beta+yo)/(1-m**2*beta**2)
    endif

tag= 1

    betr= phi + 90
    aa= phi*phi**(-t)*betr**t
    bb= betr*betr**(-t)*phi**t
    if (bb.lt.0.0001) then
        bb= 0.0
    endif
    cc= (-1)**t
    do 30 theta= aa, bb, cc
        xp= rminor*cos(theta*pi/180)
        yp= rminor*ecc*sin(theta*pi/180) +cy
        x= xp*cos(angle) - yp*sin(angle) +xs
        y= xp*sin(angle) + yp*cos(angle) +ys
        if ((x.gt.xlo).and.(x.lt.xhi).and.(y.gt.ylo).and.(y.lt.yhi))
+ then
            if (flag.eq.0) then
                write (10,9) 'POLYLINE'
                write (10,6) 8
                write (10,13) '0'
                write (10,6) 66
                write (10,7) 1
                write (10,6) 10

```

```

write (10,14) '0.0'
write (10,6) 20
write (10,14) '0.0'
write (10,6) 30
write (10,14) '0.0'
write (10,6) 70
write (10,7) 1
write (10,6) 0
mark=0
flag= 1
endif

write (10,15) 'VERTEX'
write (10,6) 8
write (10,13) '0'
write (10,6) 10
write (10,4) x
write (10,6) 20
write (10,4) y
write (10,6) 30
write (10,14) '0.0'
write (10,6) 0
lasttag= tag
tag= 0

```

- c Now, add the points of the ellipse which lie on the borders of the
c quadrant of the hologram.

```

elseif ((x.lt.xlo).and.(tag.eq.0)) then
  y= ((y-ylast)/(x-xlast))*(xlo-xlast)+ylast
  x=xlo
  write (10,15) 'VERTEX'
  write (10,6) 8
  write (10,13) '0'
  write (10,6) 10
  write (10,4) x
  write (10,6) 20
  write (10,4) y
  write (10,6) 30
  write (10,14) '0.0'
  write (10,6) 0
  tag= 1

```

```

elseif ((x.gt.xhi).and.(tag.eq.0)) then

```

```

    y= ((y-ylast)/(x-xlast))*(xhi-xlast)+ylast
    x= xhi
    write (10,15) 'VERTEX'
    write (10,6) 8
    write (10,13) '0'
    write (10,6) 10
    write (10,4) x
    write (10,6) 20
    write (10,4) y
    write (10,6) 30
    write (10,14) '0.0'
    write (10,6) 0
    tag= 1

elseif ((y.lt.ylo).and.(tag.eq.0)) then
    x= ((x-xlast)/(y-ylast))*(ylo-ylast)+xlast
    y= ylo
    write (10,15) 'VERTEX'
    write (10,6) 8
    write (10,13) '0'
    write (10,6) 10
    write (10,4) x
    write (10,6) 20
    write (10,4) y
    write (10,6) 30
    write (10,14) '0.0'
    write (10,6) 0
    tag= 1

elseif ((y.gt.yhi).and.(tag.eq.0)) then
    x= ((x-xlast)/(y-ylast))*(yhi-ylast)+xlast
    y= yhi
    write (10,15) 'VERTEX'
    write (10,6) 8
    write (10,13) '0'
    write (10,6) 10
    write (10,4) x
    write (10,6) 20
    write (10,4) y
    write (10,6) 30
    write (10,14) '0.0'
    write (10,6) 0
    tag= 1

```



```
endif
xlast= x
ylast= y

30 continue
if ((lastag.eq.1).and.(tag.eq.0)) then
  write (10,15) 'VERTEX'
  write (10,6) 8
  write (10,13) '0'
  write (10,6) 10
  write (10,4) x
  write (10,6) 20
  write (10,4) y
  write (10,6) 30
  write (10,14) '0.0'
  write (10,6) 0
endif

20 continue
if (mark.eq.0) then
  write (10,15) 'SEQEND'
  write (10,6) 8
  write (10,13) '0'
  write (10,6) 0
endif

10 continue
return
6 format (I3)
7 format (I6)
9 format (A8)
13 format (A1)
14 format (A3)
15 format (A6)
4 format (F11.7)
end
```

END

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FIN