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Aerodynamic Characteristics of Frost Roughness
by
Mark Alan Lawrysyn, B.Eng.

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

Department of Mechanical and Aeronautical Engineering

Carleton University
Ottawa, Ontario

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**The undersigned hereby recommend to
the Faculty of Graduate Studies and Research
acceptance of the thesis,**

Aerodynamic Characteristics of Frost Roughness

submitted by

Mark Alan Lawrysyn, B.Eng.

**in partial fulfilment of the requirements
for the degree of Master of Engineering**

Chair, Department of Mechanical and Aeronautical Engineering

Thesis Supervisor

Carleton University

30 August 1989

ABSTRACT

Previous research on roughness elements in boundary layer flow has only been able to present a first order approximation of the aerodynamic characteristics of nocturnal hoar frost. Wind tunnel tests of actual frost in turbulent flow were carried out after acquiring and preserving six specimens of frost on aluminum plates. Functions for the shift in the log law dependent on a three dimensional spacing parameter were determined for the frost samples. The results indicate that frost crystals create a bluntness similar to that created by a flat plate facing the flow and having the same dimensions as the frost roughness element.

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List of Symbols

Symbol	Description
A	Law of the wall slope
A_p	Roughness element frontal area :a
A_s	Roughness element wetted area of windward surface
B	Law of the wall intercept
ΔB	Shift of the law of the wall intercept
C	Law of the wall intercept with surface roughness
C_f	Coefficient of friction
D	Roughness element relative spacing
h	Height of pitot tube tip
H	Shape factor
k	Roughness element height
k_f	Frost roughness height
k_s	Sand roughness height
L	Length in two dimensional spacing parameter
P_c	Wind tunnel contraction static pressure
r	Pipe radius
s	Two dimensional roughness element length
T_{dp}	Dew-point temperature
T_{fog}	Fog formation temperature
T_{fp}	Frost point temperature
u	Velocity
U	Freestream velocity
u_τ	Friction velocity
$\Delta u / u_\tau$	Log law shift
w	Weighting factor for frost growth
x	Length along wind tunnel test section
Y	Stream tube height
y	Vertical height above test section floor

Symbol	Description
α	Angle of attack
δ	Boundary layer height
δ^*	Displacement thickness
λ	Roughness element spacing parameter
λ_1	Dvorak's spacing parameter
λ_2	Simpson's spacing parameter
λ_3	Dirling's spacing parameter
ν	Kinematic viscosity
θ	Momentum thickness
ρ	Density
τ_0	Shearing stress

1.0 INTRODUCTION

1.1 Aviation Accidents Caused by Wing Contamination

"The pilot used full flap for take-off and completed a 90 degree turn after becoming airborne. A short time after he completed another 90 degree turn and raised the flaps. As the flaps retracted the aircraft sank uncontrollably into the trees. The pilot and passenger suffered minor injuries while the aircraft was almost completely destroyed. The pilot observed a layer of frost on the wings after the accident. He had failed to sweep the frost from the wings before take-off."

"The aircraft had been parked overnight and frost had accumulated on the wings. The pilot noted the frost but decided to take-off. The aircraft became airborne but safe flying speed could not be maintained and it stalled."

These accident summaries were taken from the Canadian Aviation Safety Board's Accident/Incident Data System. They represent two of the fifteen accidents that related hoar frost as a contributing factor during a six year period starting in 1976.

1.2 Effects of Frost Roughness

There exists an obvious need for an enhanced understanding of the effects of wing contamination on the aerodynamic characteristics and performance degradation of aircraft. Investigation is required in several areas including roughness effects on drag and on boundary layer transition, allowable limits of roughness, airfoil sensitivity and revised aircraft operating procedures for flight with contaminated wings.

Surface roughness in a turbulent flow will increase the frictional coefficient (or wall shear stress) causing an increase in profile drag. This is primarily due to form drag on the roughness elements. These roughness elements will also tend to trip the boundary layer causing an early transition

from laminar to turbulent flow and will also cause an increase in kinetic energy removal from the boundary layer flow and could possibly cause leading edge separation. These effects are illustrated in Figure 1.1. The consequences are a decrease in the maximum lift coefficient with a stall at a much lower angle of attack compared to a clean wing.

Figure 1.2 shows the dramatic decrease in the maximum lift coefficient and increase in the drag coefficient of a typical airfoil with a rough upper surface compared to a clean airfoil. Other tests done on airfoil sections in wind tunnels indicate that drag may be doubled and the maximum lift degraded by a third.

Wind tunnel tests done on contaminated airfoils are suitable for determining the sensitivity of the airfoil to roughness effects. They can accommodate trailing edge flaps and leading edge devices for comparison of the various configurations used on the airfoil. Most new airfoil section analysis includes performance evaluations with certain degrees of roughness applied to the surface.

It has been suggested by several agencies that removal of all surface contamination, such as frost, may not be a necessary or a required action before take-off. Allowable limits of frost on wings might be determined in terms of a maximum frost height or the degree of frost removal along the wing chord. That is, since flow near the leading edge is more sensitive to roughness, only partial clearing of the wing might be required. This would be very appealing to commercial aircraft operators who spend substantial resources in aircraft deicing. Deicing fluids also tend to be non-biodegradable and can create a serious pollution problem at airports.

It may not be possible or practical to remove frost or other contaminants in certain circumstances. These would include military operations, medical evacuation, or operations from remote locations with limited deicing facilities. These cases would require amended take-off and climb out procedures.

During the take-off phase, an aircraft would require more thrust and/or runway length to reach the minimum take-off speed due to the increased drag caused by the surface contaminants. An increased minimum speed at lift-

off would not require an excessive angle of attack during the initial phase of the flight. If the rotation rate or angle of attack is excessive, the wing will approach the stall causing the aircraft to over-run the runway or causing a substantial decrease in the climb gradient.

Guidelines have been developed by some aircraft manufacturers but there has been some reluctance in this area. Since a commercial aircraft is certified for flight only if its wings and control surfaces are clean, publishing guidelines for operations with contaminated wings might encourage violations of this regulation. It may also cause liability claims to be made against the aircraft manufacturer if an accident did occur while modified operating procedures were used.

1.3 Thesis Objectives and Outline

There has been a substantial amount of work done on the aerodynamic effects of surface roughness on flat plates, pipes and airfoil shapes. Studies have investigated "simulated" hoar frost on airfoils in wind tunnels and have modelled the effects with computer programs. In each case the "simulated" frost could only be taken as a first order approximation to the actual crystalline ice structure that would occur on an aircraft. That is, all previous studies on frost have simulated the height but not the density, spacing, structure or shape of actual hoar frost. Experiments to determine the aerodynamic characteristics (effective height and density) of actual frost would therefore be appropriate.

The objective of this thesis was to develop a procedure to preserve actual naturally occurring hoar frost and to experimentally evaluate its aerodynamic effects on turbulent boundary layer flow.

The basic theory of forced and free convection formation of frost is outlined in Chapter 2. Chapter 2 also covers evaluation and prediction of roughness effects in turbulent flow and includes a review of previous work on the aerodynamic effects of frost. Chapter 3 covers the description and

calibrations of the experimental apparatus used to determine the boundary layer profiles. Chapter 4 outlines the procedure used in acquiring and preserving the frost specimens. The wind tunnel testing procedure and data reduction techniques are also evaluated in this chapter.

Chapters 5 summarizes the aerodynamic characteristics of the six frost specimens tested and compares these results to other types of surface roughness. Chapter 6 contains a discussion of the wind tunnel flow quality, the results and their significance, practical applications of the results and suggestions for further study. The conclusions of the experiment are summarized in Chapter 7.

2.0 THEORY

2.1 Frost Formation

The formation of frost is brought about by complex heat and mass transfer phenomena at a surface. Frost will tend to form on a cold surface whose temperature is below both the freezing point and the dewpoint of the surrounding air. Frost growth is affected by the humidity of the air, the available nucleation sites on the surface and the rate and mechanism of the heat transfer at the surface.

Nocturnal frost is caused primarily by radiation cooling. The surface can cool faster than the surrounding air, allowing it to drop to the frost point temperature. Radiation cooling to the night sky is particularly effective on cloudless nights. Still air (no wind) conditions will decrease the convective heat transfer from the surrounding air to the plate, allowing the surface to reach lower temperatures than the air.

Frost may also form by convection on a very cold surface. If an aircraft has been operated at high altitude for a long period the fuel will be cooled and the fuel cells may act as a heat sink. Descent through warmer and moister air may result in frost formation on the surface. A similar situation can occur for cryogenic fuel tanks as on the Space Shuttle or on an aerospace plane. In these cases, fogging in the boundary layer will occur and create a source for water droplet condensation on the surface. The fog will consist of supercooled water droplets (water in liquid form but below the freezing temperature). The fog point temperature is dependent on the Schmidt number, air temperature and the saturation ratio for fog nucleation. The fog point temperature may be 10°C lower than the dewpoint temperature and the actual frost point will occur between the two.

A nucleation site is required to provide an orientation from which the crystalline structure can begin to form. Without such a starting point, the moisture could remain in a supercooled form and not form into a frost crystal. Nucleation sites for frost would usually be smaller than $5\ \mu$ and could consist of

smoke or dust particles that have settled on the surface. A dull or aged surface would also contribute nucleation sites.

Deitenberger (1981) proposed that a weighting factor (w) proportional to the available nucleation sites could be determined in order to model the formation and growth of frost. The weighting factor would typically have a value between 0 and 1. Determination of the frost point temperature would take the form :

$$T_{fp} = wT_{dp} + (1-w) T_{fog} \quad (2.1)$$

Equation 2.1 implies that for frost to occur on a surface without any nucleation particles, the surface frost point would be the temperature where fogging occurs in the boundary layer. This would result in the frost forming by reverse sublimation.

When the frost first begins to nucleate, the dendrites are spherical and are 5μ to 10μ in diameter. After the frost grows to 20μ to 50μ , the dendrite formations will intermesh creating "ice trees". If the temperature of the surface continues to drop below the frost point temperature, the formations will increase in density and thickness. The frost will also act as an insulating material during the growth process and eventually an equilibrium point will be reached where the surface temperature stabilizes and the surface radiation and conduction effects are decreased.

Photo Plate 2.1 shows photos of 1 cm thick frost collected on polyethylene sheeting. Borys (1987) and Dietenberger (1982) observed accumulation rates exceeding 0.05 gm/cm^2 by mass and 3 mm/hr in thickness, depending on prevailing conditions.

2.2 Roughness Effects in Turbulent Boundary Layers

Laminar flow will develop a predictable boundary layer profile on a flat plate. This Blasius profile will be maintained even after the flow is disturbed by an obstacle if the obstacle size is small compared to the boundary layer thickness and the Reynolds number is sufficiently low.

In turbulent flow there does not exist a convenient or precisely predictable boundary layer profile. Most turbulent boundary layer profiles can be approximated by power-law curves having exponents between 1/3 and 1/10.

Clauser (1954) developed the defect law which yields a universal plot of the outer portion of flat plate turbulent boundary layer profiles. He noted that the wall shear stress has a significant effect on the flow as it is a representative measure of the energy supplied to the turbulence. The wall shear stress for turbulent flow is dependent on the Reynolds number and the degree of wall roughness. The wall shear stress, τ_0 , can be represented in non-dimensional form by a skin friction coefficient:

$$C_f = \tau_0 / (1/2 \rho U_e^2) \quad (2.2)$$

It also can be reduced to dimensions of velocity squared by dividing it by density to give a shear or friction velocity, defined as follows:

$$u_\tau^2 = \tau_0 / \rho \quad (2.3)$$

Clauser noted that boundary layer profiles in zero pressure gradient would have identical non-dimensional plots of $(u - U_e) / u_\tau$ versus (y/δ) . This is the so-called defect law. It is obtained as follows:

$$(u/U_e - 1) \cdot \sqrt{C_f/2} = (u - U_e) / u_\tau \quad (2.4)$$

where

$$C_f/2 = \tau_0 / (\rho U_e^2) = (u_\tau / U_e)^2$$

Figure 2.1 shows the defect law using boundary layer profiles measured with varying degrees of wall roughness and Reynolds number. Figure 2.1 also indicates that wall roughness does not affect the defect-law profiles. Thus the only effect of roughness on the outer part of the boundary layer is through its effect on the wall shear stress or on u_τ . That is, in the outer regions:

$$(u - U_e) / u_\tau = f[y/\delta] \quad (2.5)$$

with the same $f[y/\delta]$ for both smooth and rough walls.

In examining the flow near the wall, Clauser determined that the turbulence in the outer region would be sufficiently far away that it would not directly affect the structure of the near-wall flow. The velocity profile in the near-wall region would be described by a function such that:

$$u = f[y, \rho, \nu, \tau_0] \quad (2.6)$$

By measuring the boundary layer profile in the near-wall region a laminar sublayer was observed. The laminar sublayer thickness, y_{lam} , is such that

$$y_{lam} u_\tau / \nu = 5$$

For $5 < y u_\tau / \nu < 50$ there exists a buffer layer where the flow changes from laminar to fully turbulent.

Experimental data plotted in Figure 2.3 indicated a linear relationship in the laminar sublayer given as:

$$u/u_\tau = u_\tau y / \nu \quad (2.7)$$

The above relationship will be valid for values of $u/u_\tau < 5$.

The log law can be developed by equating the defect law to the law of the wall. For $yu_\tau/\nu > 50$ the velocity profile is found to be logarithmic. This assumes that both laws apply in a certain overlap region. Thus,

$$(u - U_e)/u_\tau = F_1[y/\delta]$$

or

$$u/u_\tau = F_1[y/\delta] + U_e/u_\tau \quad (2.8)$$

and the wall law:

$$u/u_\tau = F_2[y u_\tau/\nu]$$

or

$$u/u_\tau = F_2[y/\delta \cdot \delta u_\tau/\nu] \quad (2.9)$$

By examining Equations 2.8 and 2.9, it was determined that the only way in which the two equations can be identical is if the functions are logarithmic, as follows:

$$(u - U_e)/u_\tau = A \log(y/\delta) + C_1 \quad (2.10)$$

and

$$u/u_\tau = A \log(u_\tau y/\nu) + C_2 \quad (2.11)$$

As shown in Figure 2.2, the experimental data supports this result since they plot the log law in the form:

$$u/u_\tau = A \log(u_\tau y/\nu) + B \quad (2.12)$$

with the constants experimentally determined to be $A=5.6$ and $B=4.9$.

Surface roughness will tend to increase the wall shear stress and this results in a downward shift of the log region as shown in Figure 2.3. Experimental data collected by Clauser and others has shown that the slope of the log region remains the same but a change in intercept will occur. The degree of the shift is dependent on the nature of the roughness. Specifically,

it would be dependent on the roughness element height, the shape of the elements and on the spacing or density of the elements.

Clauser suggested a modification to the log law that would accommodate the roughness effect. The equation for the log law becomes:

$$u/u_\tau = A \log (u_\tau y / \nu) + B - \Delta u / u_\tau \quad (2.13)$$

where

$$\Delta u / u_\tau = f [u_\tau k / \nu] + C [\lambda] \quad (2.14)$$

C would be some empirical function dependent on the nature of the roughness.

Schlichting (1955) noted that the fundamental difficulty for evaluating flows over rough surfaces was the number of parameters required to describe the surface. These included geometric shape or form, spacing or distribution over the surface, and the height specified as a mean or to the peaks of the roughness elements.

The height of the roughness elements will determine the degree of skin friction caused by either the viscous shearing forces or the form drag. Schlichting refers to the extensive work done by Nikuradse (1933) on sand-roughened pipes. In these experiments measurements of flow resistance were made for circular pipes with uniform sand glued as densely as possible to the inner surface. The sand roughness values ranged from $k_s/r = 1/15$ to $k_s/r = 1/500$ where r is the radius of the pipe and k_s is the nominal diameter of the sand grains. From these studies three roughness regimes were identified.

The hydraulically smooth regime was determined to be where:

$$k_s u_\tau / \nu \leq 5 \quad (2.15)$$

In this region the pipe had the same characteristics as a smooth pipe because the roughness does not protrude through the laminar sublayer. The wall shear stress is due to the viscous shearing forces only.

In the transitional regime the sand particles would partially extend outside the laminar sublayer and the wall friction would be caused by both viscous shear and form drag on the roughness elements. This region was identified by :

$$5 < k_s u_\tau / \nu \leq 70 \quad (2.16)$$

For the fully rough regime, the roughness elements protrude far above the laminar sublayer and the skin friction is predominantly due to the form drag on the roughness elements with little contribution coming from viscous shearing forces in the sublayer. This would occur where:

$$k_s u_\tau / \nu > 70 \quad (2.17)$$

and Equation 2.14 becomes :

$$\Delta u / u_\tau = -A \log [u_\tau k / \nu] + C [\lambda] \quad (2.14a)$$

Figure 2.4 shows a correlation between various shapes and spacing to an equivalent sand roughness height. Included in this figure are the roughness elements tested by Schlichting (1955) and the corrected data by Coleman et al (1984). Schlichting suggested that by determining an equivalent sand roughness height for a given roughness shape the empirical formulas developed by Von Karman and Nikuradse could be applied. Figure 2.4 also shows the significant and unique dependence on geometric shape in correlating an equivalent sand roughness height.

2.3 Roughness Element Spacing Parameters

The spacing of the roughness elements and their geometric shape will have a significant effect on the log law intercept point. The correlation of a spacing parameter to $\Delta u/u_\tau$ or an equivalent sand roughness height have been made by Dvorak (1969), Simpson (1972) and Dirling (1973).

Dvorak developed equations to predict growth of a turbulent boundary layer over a rough surface. He suggested that the laws developed by Nikuradse were not generally suitable to determine skin friction of various roughness shapes even when catalogued with equivalent sand roughness height.

He began his analysis with more recent studies by Hama (1954) that determined a skin friction law for fully rough surfaces with zero pressure gradient given as:

$$\sqrt{2/C_f} = A \log (U_e \delta^*/\nu) + B - \Delta u_1/u_\tau \quad (2.19)$$

again with

$$\Delta u_1/u_\tau = A \log (u_\tau k/\nu) + C[\lambda] \quad (2.20)$$

Dvorak correlated various data to derive a function for $C[\lambda_1]$ dependent on the relative spacing of the the roughness elements. These relationships are shown in Figures 2.5 and 2.6 .

The spacing function was defined by Dvorak as:

$$\lambda_1 = L/s \quad (2.21)$$

where s is the chacteristic length of the roughness element and L is the distance between the elements as shown in Figure 2.6 .

The equations for the shift in the law of the wall plot were, for fully rough conditions, determined to be:

$$\Delta u_1/u_\tau = A \log (u_\tau k/\nu) + 17.35(1.625 \log \lambda_1 - 1) \quad (2.22)$$

for $\lambda_1 \leq 4.68$ and

$$\Delta u_1/u_\tau = A \log (u_\tau k/\nu) - 5.95(1.103 \log \lambda_1 - 1) \quad (2.23)$$

for $\lambda_1 > 4.68$.

The procedure was also made applicable to flows in the transitional roughness regime and modified to accept pressure gradient effects by the simple addition of a second function $\Delta u_2/u_\tau$ to Equation 2.19. Dvorak developed the above correlation using data for square two dimensional roughness elements such as those shown in Figure 2.5 .

Simpson (1972) showed that Dvorak's correlation could also be applied to three dimensional roughness elements by redefining the spacing parameter. Simpson noted that for flow in the fully rough regime, skin friction is predominantly caused by form drag. Form drag is usually related to the frontal area for blunt bodies. He proposed that the parameter λ_2 taken as the ratio of total surface area to total roughness frontal area normal to the flow.

Figure 2.7 shows the correlation of the change in intercept parameter, $C [\lambda]$, to Simpson's spacing parameter, λ_2 . In this case $C [\lambda]$ remains as defined in Equation 2.20. The figure also includes Dvorak's functions for $C [\lambda]$ as given in Equations 2.22 and 2.23. It can be seen that these equations still correlate the data when Simpson's definition of λ is used.

Dirling (1973) developed a spacing parameter that took into account the surface distribution or density, the height of the element, and the bluntness of the element. Dirling noted that Schlichting's catalog of roughness, element shape and spacing to equivalent sand height (k_s) could be correlated with a spacing parameter defined as:

$$\lambda_3 = D/k (A_p/A_s)^{-4/3} \quad (2.24)$$

$1/D^2$ is equal to the number of roughness elements per unit surface area or, more specifically, D^2 would be the average area $D \times D$ required for one roughness element as shown in Figure 2.4. A_p/A_s is the bluntness parameter and is a measure of the three dimensionality of the roughness element. A_p is the projected area of the element facing the freestream velocity vector. A_s is the wetted surface area seen by the flow on its windward side. For a right angle roughness element this ratio would be $A_p/A_s = 0.5$ and spherical segments and cones would have $A_p/A_s = 0.42$

Figure 2.8 shows Dirlings correlation of equivalent sand roughness height to the spacing parameter λ_3 . From this figure Dirling determined the two regimes for equivalent sand heights to be:

$$k_s/k = 0.0164 \lambda_3^{3.78} \quad \text{for } \lambda_3 < 4.93 \quad (2.25)$$

and

$$k_s/k = 139 \lambda_3^{-1.90} \quad \text{for } \lambda_3 \geq 4.93 \quad (2.26)$$

It should be noted that several of the points used on Figure 2.8 were taken from Schlichting's uncorrected data.

2.4 Determination of Wall Shear Stress

Clauser (1953) replotted Figure 2.2 with u/U_e as an ordinate instead of u/u_τ . This resulted in the Clauser Plot shown in Figure 2.9. It includes a series of universal boundary layer curves with C_f as a parameter. When boundary layer profile data are plotted on this chart the skin friction can be determined by where the data plot relative to the various C_f plots.

A similar approach can be applied to determining C_f for rough wall boundary layers by modifying Equation (2.13) into:

$$u/U_e = A(u_\tau/U_e) \cdot [(\log U_e y/\nu) + B/A - \Delta u/u_\tau] \quad (2.27)$$

or

$$u/U_e = A(u_\tau/U_e) \cdot (\log U_e y/\nu) + A(u_\tau/U_e) \cdot (B/A - \Delta u/u_\tau)$$

The slope from such a plot would be equal to $A(u_\tau/U_e)$ or $A\sqrt{C_f/2}$.

Unfortunately, for rough walls this method relies on comparison of slopes only and the determination of C_f is consequently rather inaccurate.

The alternative method for determining the skin friction coefficient from experimental data would be to use the momentum integral equation:

$$d\Theta/dx = C_f/2 - [(H+2) \cdot (\Theta/U_e) \cdot (dU_e/dx)] \quad (2.28)$$

This method is also subject to inaccuracy since $d\Theta/dx$ is quite sensitive to small three-dimensional effects, namely flow convergence or divergence, in the measured flow.

2.5 Review of Previous Work on Aerodynamic Effects of Frost

Chen and Rohsenow (1964) examined the high heat transfer rates and pressure drop within a pipe roughened by frost. In their experiments they compared photographs of frost formed on a cold plate to photographs of sand of varying grain sizes. This was done to correlate an equivalent sand roughness used for comparison with the rough pipe pressure loss research done by Nikuradse.

They determined that the roughness height of frost was approximately proportional to the thickness during its initial growth. Further increases in frost thickness did not increase the roughness height. That is, the underlying

frost layer would create a relatively smooth base and not contribute to a roughness height. It was hypothesized that the frost would eventually reach and maintain a steady state roughness height independent of its total thickness.

Initial frost formation would be dependent on availability of nucleation sites and the frost would be non-uniform in composition. For the case where the thermal conductivity of the frost particles attached to the surface is greater than the conductivity of the air, further condensation will occur on the frost. The height of the frost roughness will increase and at some point it will create sufficient turbulence in the flow to increase the eddy conductivity of the air. Finally the frost would continue to thicken but its roughness height would remain stable.

Figure 2.10 shows a comparison of roughness and thickness observed by Chen and Rosenhow. During the initial growth roughness height is equal to frost thickness but eventually the roughness height reaches some constant value even if the thickness continues to increase. It should be noted that these experiments were done where a frost layer was precipitated by forced convection in a tube by maintaining the wall at a temperature below the frost point. The wall was cooled by conduction only.

Langston (1968) did preliminary calculations on the aerodynamic effects of frost with respect to lift and drag behavior of aircraft wings. His results were based on limited data and were useful to indicate the order of magnitude of frost roughness effects. These calculations were based on an assumed equivalent sand roughness height of 1.66 times the frost roughness height. This value was suggested in a 1944 reference on the effects of camouflage paint roughness on drag.

Langston also referred to operational trials of military aircraft (F-86 Sabre and B-47 Stratojet) that were flight tested with varying frost layers up to 6 mm or 7 mm thick. These tests were done to determine if frost contamination required any change in the aircraft take-off or climb speeds referred to in the operating handbook. They concluded that the aircraft experienced little or no adverse affect on take-off performance or handling

characteristics. The report also stated that the test results would not justify a recommendation that the aircraft not be defrosted before flight.

Dietenberger (1981) determined an overly conservative equivalent sand roughness height based on a paper by Dirling (1973). Dirling developed an explicit function using mean roughness height, relative spacing and the shape of the roughness element. The estimate developed from this approach was,

$$k_s = 6.8 k_f \quad (2.29)$$

Dietenberger (1983) applied a corrected heat transfer coefficient to Chen and Rohsenow equations to determine an equivalent sand roughness height as

$$k_s = 1.66 k_f \quad (2.30)$$

This relationship was in agreement with other experimental data where the increase in convective heat transfer coefficients in forced convection was attributed to frost surface roughness. Dietenberger (1984) also stated that for typical nocturnal frost the equivalent aerodynamic sand grain roughness is not generally dependent on frost density.

Nelson (1979) determined that airfoil roughness can change both performance and control characteristics of an aircraft. His wind tunnel tests indicated that the amount of degradation would be dependent on the nature of the surface contamination and the airfoil sensitivity to roughness. Trim and stability characteristics could be changed by an early transition on an airfoil caused by roughness. This earlier transition could result in thickening of the boundary layer with possible flow separation near the leading edge or trailing edge. In the case of a canard type aircraft the reduction in lift would result in a nose down pitching increment and diminished elevator effectiveness.

Dietenberger (1984) developed empirical relationships for drag, lift, and angle of attack penalties due to hoar frost, snow adhesion and wavy water film

on an airfoil surface. Maximum lift loss and reduction in stall angle was related to the mean height of the contaminant, amount of coverage over the aircraft and the Reynolds number based on chord length. This study determined that typical airfoils for both large and small aircraft would experience serious losses in lift with frost roughness heights of 1 mm or less.

2.6 Flight Tests With Simulated Ground Frost

During 1982 and 1983 the Boeing Commercial Airplane Company developed a test program to evaluate the effects of frost on drag increases, stall characteristics, take-off characteristics, lift loss in ground effects and climb performance degradation. Simulated frost was applied to the upper wing surface of B-737, B-757 and B-767 aircraft. It consisted of an anti-slip safety walk adhesive material with a layer of epoxy potting material roughened with a texture paint roller. Three roughness heights of 0.36 mm, 0.76mm, and 1.27mm were tested in the program.

The flight test results showed substantial reductions in climb performance and decreases in maneuvering margins as indicated in Figure 2.11 . The results also indicated that during the critical phase of take-off a stalling condition may occur at speeds above normal stalling speeds. This could occur without any indication from the stick-shaker stall warning. The report concluded that increased take-off speeds and lower rotational rates would improve safe take-off margins during conditions where the wings are contaminated.

3.0 EXPERIMENTAL APPARATUS

3.1 Wind Tunnel and Test Section

The present boundary layer experiments were performed in the low speed wind tunnel at Carleton University. This is a continuous closed circuit wind tunnel with a 51 X 76 cm cross section. It has a top speed of 70 m/s although it was operated at 50 m/s during the experiments. This resulted in a Reynolds number of approximately 5.5×10^6 based on the available chord length. The working section was previously used for boundary layer research by Nituch (1972) and measured 183 cm in length with a 3 cm breather slot at its downstream end.

The floor for this test section consisted of a 5/8" thick aluminum plate. The underside was drilled and tapped at five locations to accommodate the traversing gear and pitot tube. The pitot tube's vertical stem passed through 1/8 inch ports drilled through the test section floor. Figure 3.1 shows the dimensional locations of the five boundary layer traversing stations. Five static taps were fitted into the plywood ceiling above and slightly upstream of the pitot ports along the test-section centerline.

The various frost specimens were preserved on 1/8 " thick aluminum plates by the method outlined in Chapter 4. These plates were slightly narrower than the test section to allow for easy placement and removal. Each plate was firmly fixed to the test section floor by double sided tape and four pairs of screws offset 25 cm from the centerline. Each hole in the plate was countersunk so that no part of the screw extended into the boundary layer and putty was applied to create a smooth surface in these areas.

The traversing gear is shown in Photo Plate 3.1 and consisted of a small stepper motor driving a threaded brass rod. The threaded rod acted as a power screw driving a traversing plate. The pitot tube stem was attached to this plate by means of a threaded grip. Calibration of the operating system was done with a depth dial gauge having a travel of 25 mm and was accurate to $\pm$

0.01mm. The positioning accuracy of the traversing gear was ± 0.02 mm through a travel of 25 mm.

An open loop control system was used to vary the pitot tube height during the experiments. The controller for the system accepted binary pulses from the printer port of a micro computer. The stepper motor driver would integrate these signals and step the motor up or down. Approximately 1800 pulses were required to move the traversing plate 1 cm. This allowed accurate steps as small as .025 mm (.001 inches) to be made.

This method of controlling the traversing of the pitot tube was totally independent of the data acquisition system. Specifications and wiring diagrams for the system are included in Appendix D:

3.2 Data Acquisition

A TAURUS data acquisition system was used to record a reference pressure and the dynamic pressure at any height within the boundary layer. The reference pressure was taken as the pressure difference between a wall static pressure tap in the settling chamber of the wind tunnel (P_{C1}) and a static tap in the contraction just ahead of the test section (P_{C2}). This difference is typically used in low speed wind tunnels as the reference quantity and is known as the contraction pressure difference, ($P_{C1}-P_{C2}$). The dynamic pressure in the boundary layer was taken as the difference between the reading of the pitot tube and that of the static pressure from the local tap in the ceiling of the test section.

The TAURUS data acquisition system was set up such that it had an analog input voltage range of ± 2.5 volts. A gain of unity was applied to these inputs which together with 12 bit A/D converter resolution resulted in an accuracy of 0.6 millivolts. This accuracy was confirmed with calibrations done with a voltmeter connected in parallel to the transducer outputs. Typical data inputs from the pressure transducers ranged from 0.18 volts to 1.1 volts. Two analog input channels were scanned with each channel achieving a

sampling rate of 11 samples per second. The test set-up and data acquisition system are shown in Photo Plate 3.2 .

3.3 Pressure Transducers

The pressure differences were measured with two Setra pressure transducers having a range of ± 0.34 kPa (± 0.5 psid) with a maximum DC voltage output of ± 2.5 volts. The transducers were calibrated during the experiments in varying atmospheric conditions of temperature, humidity and ambient pressure. The calibrations, shown in Figure 3.2 , indicated a linear function between the sensed differential pressure and the transducer output voltage. These results closely matched the calibrations done by Yaras (1987) and Amrud (1985) on the same transducers.

3.4 Pitot Tubes

Pitot tube tips were constructed from 1.06 mm outside diameter stainless steel tubing. The tubing was flattened into an oval shape and then sanded and polished on the upper and lower surfaces. The tips were then soldered into 1/8 inch brass tubing.

Photo Plate 3.3 shows the two types of pitot tubes used in the experiment. The dimensions of the pitot tube tip were 0.52 mm in height and 1.3 mm in width as indicated in Figure 3.5. The longer pitot tube was used at the furthest downstream station (Station 5) in order for the pitot tube tip to be placed sufficiently forward of the interference caused by the test section breather slot. The pitot tube with the shorter tip was used at Stations 1 to 4.

3.5 Miscellaneous Apparatus

Other equipment used included a multi-tube vertical water manometer to monitor contraction pressure difference and the static pressure distribution along the test section, a barometer to record ambient pressure, and a voltmeter to monitor the analog input to the TAURUS data acquisition system.

4.0 EXPERIMENTAL PROCEDURE

4.1 Natural Frost Acquisition and Preservation

Extensive boundary layer measurements of natural hoar frost cannot be made in wind tunnels or on flight test vehicles due to inevitable dissipation of the frost in a forced convection environment. This requires the frost to be either artificially simulated or preserved in such a manner as to retain its geometric characteristics.

Samples of frost were acquired on flat 1/8 inch thick aluminum plates measuring 1.83 m X 0.76 m. To produce frost on the plates, they were laid outdoors on a 2.5 cm thick layer of styrofoam insulation and inclined 15° to 20° from the horizontal facing away from nearby buildings. The styrofoam was used to limit the heat flux caused by conduction to the underside of the plate. For free convection the Grashof number of a horizontal plate is less than that for a vertical plate so a near horizontal condition was used. The Nusselt number and consequently the rate of heat flux is a function of the Grashof number multiplied by the cosine of the inclination of the plate. This increase in angle of the plate would allow a lower surface temperature but would result in greater radiation heat transfer from nearby buildings. 15° to 20° inclination was considered a fair compromise between increasing the free convection and decreasing the radiation configuration factor. Free convection is also the mechanism by which mass transfer from the moist air to the frost formation will occur.

The original emissivity of the aluminum plates was quite low due to their shiny surface finish. A light application of high temperature black spray paint was applied to most of the specimens. The dull black finish greatly increased the emissivity and a light application of the paint also supplied nucleation sites for the frost. Thick applications of the paint did not noticeably increase frost growth on initial samples but did cause the finish to run and crack after application of the preserving solution.

The frost samples were preserved using Monsanto FORMVAR, a polyvinyl formal plastic material, dissolved to form a 0.5 % solution by weight with ethylene dichloride. This solution would soak into the porous ice crystal structure and slowly evaporate leaving a thin plastic film cured in the same shape as the original crystal. Photo Plate 4.1 shows how well the preservation of frost crystals replicates the original form and structure. This technique was originally developed by Kind (1987) after noting that Schaefer (1970) used a similar technique to preserve snow crystals.

Attempts to use spray bottles or atomizers to apply the solution were not successful due to the low temperatures and clogging of the nozzle. A more effective method was to incline the plate slightly and carefully pour the solution along the upper edge. The solution would then seep down the plate with the excess running off. This method did not damage the frost at the edge of the plate as long as the solution was at a lower temperature than that of the plate. Approximately one litre of the solution was required to preserve one plate with thick frost. Leaner solutions were applied to light frost samples and required curing times of less than two hours.

Rogers (1987) suggested several other methods of preserving snow crystals used in meteorological research. A plate could be pre-coated with a layer of FORMVAR and allowed to cure. After snow had fallen on it, it would be "developed" by exposing the plate to a solvent vapour environment of ethylene dichloride or ether. Other methods included dripping or painting the solvent over the ice crystal structure. Rogers also suggested using KRYLON, a spray fixative used by artists, as an alternative preservation material.

4.2 Frost Roughness Parameters

Frost height could be determined using several methods. Precise measurements can be made with a scratch microscope but the instrument would be awkward to use except along the edge of a plate. Langston (1968)

suggested a wedge-like device made of perspex or plexiglass. Examples of the device are shown in Photo Plate 4.2. The device is slightly beveled on one side with scale markings placed on it. When drawn over a surface the height of the frost is noted from the scale reading where the dendrites are not disturbed. It requires a flat surface and a careful technique to get accurate values.

The method that worked very well with the preserved frost samples required a tongue type feeler gauge and a watchmaker's eyepiece. The stack of selected feeler gauge tongues were placed adjacent to a frost crystal. The eyepiece allowed a magnified skewed view of the two heights for comparison. This was a quick and simple method that did minimal damage to the frost sample and accuracy was estimated to be ± 0.01 mm. Frost crystal density or spacing was not always consistent over the aluminum plates but the average peak height of the crystals did not vary significantly. After determining the height of a single typical crystal the feeler gauge tongues were compared with other crystals along the length of the plate. The peak frost height would usually vary 5% to 10% along the total length of the frost plate.

Other parameters of the frost such as spacing and crystal size could be obtained by evaluating the series of photographs taken of each specimen. The photographs were taken using a 35 mm SLR camera with a macro lens. Dvorak's spacing parameter, λ_1 , was limited to two dimensional roughness elements. This parameter could not be applied to frost roughness due to the three dimensionality of the frost, so the spacing parameter λ_3 , suggested by Dirling was applied.

As defined in Equation 2.24, D is determined from the frost specimens by simply counting the number of crystals per unit area from several photographs. D cm $\times$ D cm would be the average area occupied by one crystal. K_f was taken as the peak frost roughness height. The bluntness parameter, A_p/A_s , could not be easily determined from the photographs due to the intricate and complex structure of the crystals. This value would be determined by fitting the experimental data to functions taken from other test data on surface roughness elements.

4.3 Boundary Layer Measurements

The aluminum plates with preserved frost specimens were solidly fixed to wind tunnel working section floor. Each test started at station number five, this being the farthest downstream point. A 1/8 inch hole was drilled through the plate to accommodate the pitot tube's vertical stem. Starting at the rear-most position and working forward did not require a plugging of the previous holes that would otherwise create an area of suction or sink along the flow nor would it destroy the section of frost directly above the hole's location.

With the traversing gear fixed to the underside of the wind tunnel test section the pitot tube's vertical stem would be connected to the traversing plate. The pitot tube would then be lowered until its tip came into contact with the plate's surface. Photo Plate 4.3 shows the pitot tube placement at the start of the test run. The initial steps would move the pitot stem but the flexible pitot tube would remain on the surface. The first step into the boundary layer profile would be identified by an increase in pressure sensed as the pitot tube moved above the surface. This method was more effective than trying to position the pitot tube visually so it just touched the surface. Figure 4.1 shows a schematic diagram of the initial setting of the pitot tube and its flexure during the initial traversing steps.

The accuracy of the initial pitot tube vertical position would be within half of the step size. In most cases, this was substantially less than the roughness height of the frost. A typical step size was 0.03 mm and the frost roughness heights varied from 0.2 to 0.8 mm.

Appendix C contains the source code for the data acquisition program. Initial inputs consisted of barometric pressure, air temperature and zero reading from the pressure transducer output voltage. The user was prompted for an initial step size and total height for traversing. The step size was scheduled to increase 5% per step in order to obtain seventy to eighty points within the boundary layer. The initial step size varied from .001 inches at

Station 1 to .002 inches at station 5. At least fifteen readings were made outside the boundary layer and averaged to determine free stream velocity.

Contraction pressure difference was recorded concurrently with the boundary layer measurements. This was done to take into account any effects of minor wind tunnel flow perturbations during testing. The wind tunnel freestream velocity declined slightly during the test runs due to an increasing free stream temperature and small changes in motor power. At completion of a run, final temperature, manometer contraction pressure and pressure transducer zero values were recorded. During each run the scheduled or computer controlled traversing height was compared with the actual displacement of the traversing plate using the depth dial indicator. Table 4.1 includes the typical values of the traversing heights taken during a test run. The actual traversing distance was compared to the scheduled traversing distance from the computer.

Table 4.1 Comparison of computer scheduled and actual pitot tube traversing distances.

Step No.	Y _{actual} (mm)	Y _{scheduled} (mm)
0	0.00	0.00
5	0.19	0.17
10	0.42	0.40
21	1.22	1.24
30	2.31	2.33
43	5.03	5.04
59	11.90	11.90
68	18.86	18.88
69	19.85	19.86
70	20.87	20.89
71	21.94	21.97

A sample output of a test run is included in Appendix C. The actual point where the pitot tube first leaves the surface could be easily determined by the significant increase in pressure sensed by the pitot tube.

Figure 4.2 shows the typical scatter of the transducer output voltage over three steps with sixty seconds of sampling each. It was noted that the system required five seconds for the readings to settle out to the mean value and that averaging these readings for greater than twenty seconds did not alter the mean value. The computer program set the waiting period at ten seconds and sampling time at thirty seconds.

4.4 Data Reduction Techniques

The experimental data were processed through the program DATA.FOR included in Appendix C. This program determined the average velocity and dimensionless velocities within the boundary layer. The dimensionless values for velocity were determined from the following equation:

$$\sqrt{\frac{P_{\text{pitot}} - P_{\text{static}}}{P_{c1} - P_{c2}}} \cdot \sqrt{\frac{(P_{c1} - P_{c2})_e}{(P_{\text{pitot}} - P_{\text{static}})_e}} = \frac{U}{U_e} \quad (4.1)$$

$P_{c1} - P_{c2}$ is the contraction differential pressure and $P_{\text{pitot}} - P_{\text{static}}$ is the pitot/static pressure measured at a certain point on the profile. $(P_{c1} - P_{c2})_e$ and $(P_{\text{pitot}} - P_{\text{static}})_e$ are the same values averaged from the fifteen measurements of pressure taken outside of the boundary layer.

The effects of pitot tube proximity to the wall were also included in this program. A flattened pitot tube measuring low speed flow will initially sense a lower than actual velocity with respect to the actual velocity occurring at that pitot tube centerline height. Ozarapoglu (1973) suggested the following correction to determine the actual height for the sensed pressure near a wall:

$$Y_{\text{actual}} = y + h(0.276 \log_{10}(y/h)) \quad (4.2)$$

This correction was applied to values of $y/h < 1$ and affected the first four to six points of the velocity profile depending on the initial step size

Output from the program took the form of a corrected velocity profile consisting of sixty to seventy points within the boundary layer. The

boundary layer thickness was taken at the point where u/U_e was equal to 0.995. Momentum thickness and displacement thickness were determined through numerical integration using the trapezoidal rule.

The frictional coefficients along the length of the frost plates were determined using the methods outlined in Section 2.4. Figure 4.3 shows u/U_e versus $\log_{10} Re_y$ with two sets of data from Plate 4. The frictional coefficient is determined by the slope of the log-law region of the plot. The second method of determining wall shear stress used the momentum integral equation. A fourth order polynomial was fitted through the momentum thickness points along the frost plate and then differentiated to determine $d\theta/dx$. The experimental values of shape factor and pressure gradient were then applied to Equation (2.28) to determine the skin frictional coefficient.

4.5 Application of Dvorak's Boundary Layer Prediction Method

Appendix C contains the source code for the program BLP.FOR which was used to determine turbulent boundary layer development over a rough surface. It is a modified version of an existing computer program based on Dvorak's (1969) method. This method applied the skin friction law (Equation 2.19), and an entrainment equation to determine the shape factors. The entrainment equations were taken from Head (1958) and related the boundary-layer thickness, the velocity distribution in the outer portion of the boundary layer and the freestream velocity to the rate of entrainment of fluid into the boundary layer.

The program required the initial experimental values of momentum thickness and the shape factor. The Reynolds number, chord length, roughness density, roughness element height and pressure gradient were also supplied as inputs. The momentum integral equation and Head's entrainment functions were simultaneously integrated using a Runge-Kutta routine at each step in the calculation with C_f determined by Equation 2.19. The program precisely matched the examples of calculations done by Dvorak

for various roughness heights and flows with and without pressure gradients. Frictional coefficient, momentum thickness, shape factor and boundary layer height for each of the five stations along the frost plates were determined.

The program was applied to match the data in two ways. The first matching procedure was to use the measured frost height as the input parameter for the roughness element height. Growth of the computed momentum thickness was matched to the experimental results by varying the spacing parameter λ_1 . This resulted in an equivalent spacing parameter for the frost specimen. The effect of varying the spacing parameter on the predicted boundary-layer growth is shown in Figure 4.4.

In the second matching procedure the equivalent sand roughness height was varied until measured and predicted momentum thickness growths were in agreement. Dvorak determined that the equivalent spacing parameter for sand was $\lambda_1 = 3.17$. This value was applied in the program as a constant and the roughness height parameter varied to match the experimental results. The effects of varying sand roughness heights are shown in Figure 4.5.

¹ Values for $C_f/2$ in Table 5.1 are arithmetic average of C_f values taken from all five stations. Values for u_τ are derived from averages of C_f , U_e , and ν . ΔB values were also taken from the average shift in the log law with the data from all five stations weighted equally. The average free stream velocity for in the wind tunnel was 52 m/s with the air temperature approximately 87 degrees F.

5.0 RESULTS

5.1 Experimental Test Results for Frost Specimens

Photo Plates 5.1 to 5.6 in Appendix B include the six photographs of the preserved frost specimens used in the experiments. Figure 5.1 to 5.6 show the boundary layer profiles and Clauser plots for each of the frost plates at five stations along its length. Also included is the data from a smooth, uncontaminated plate shown in Figure 5.7. The slopes of the Clauser plots were used to determine the wall shear stress as outlined in Section 2.4. This section also outlined the method used to determine C_f by applying the momentum integral equation. These points are included in Figures 5.8 to 5.14 which compare the boundary layer parameters of C_f , Θ , H and δ that were observed in the experiments to those predicted by Dvorak's method. The dashed lines in Figures 5.8 to 5.14 represent a best fit for the five points from each plate. For this reason, the start of the curves will not coincide with the first data point for the Θ and H charts. These figures show a decrease in C_f with increasing downstream distance. This would be expected since the boundary layer thickness would increase with distance, thus decreasing the relative roughness height.

Figures 5.15 to 5.21 include the law of the wall velocity distributions for the experimental data and the theoretical velocity distribution for a smooth plate using $A=5.75$ and $B=5.5$. The downward shift of the law of the wall velocity distribution was taken as ΔB which is the same as $\Delta u/u_\tau$ as given in Equation 2.20.

The results taken from the figures are summarized in Table 5.1. This table contains the average parameters from the five stations for each frost plate. The average Reynolds number for the tests was $Re_c = 5.5 \times 10^6$ for a frost plate chord length of 1.83 m.

The values for peak frost roughness height, k_f , and frost crystal spacing, $1/D^2$, were determined as described in Section 4.3. Dirling's roughness

parameter, λ_3 , is defined in Equation 2.24 and utilizes the bluntness factor, A_p/A_s , for frost crystals as outlined below in Section 5.3.

For reasons outlined in Section 2.4, the experimentally determined values for C_f had a significant scatter and an average value taken from these data points would have been inappropriate. Dvorak's Boundary layer prediction using the skin friction law and entrainment equations provided an accurate indirect method of determining C_f . The average values of C_f for each plate were then taken from the computer routine after matching of the experimental momentum thickness growth as outlined in Section 4.5. The average values for $k_s u_\tau / \nu$ were determined using C_f and the Reynolds number. $C[\lambda]$ was determined using Equation 2.20.

Table 5.1 Experimental test results from the boundary layer measurements for frost specimens.

Plate No.	k_f mm	$1/D^2$ cm ⁻²	λ_3 -	$k_f u_\tau / \nu$ --	ΔB -	$C[\lambda]$ -	$C_f/2$ --	$A_p/A_s = 0.9$ $A=5.6$
1	0.75	1.91	11.1	116.9	-6.4	-5.18	.0023	
2	0.50	5.11	10.2	74.4	-5.5	-5.01	.0021	
3	0.385	3.80	15.4	63.8	-8.3	-1.81	.0026	
4	0.37	3.17	17.5	60.1	-6.9	-3.04	.0025	
5	0.35	1.12	23.5	48.2	-3.1	-5.33	.0018	
6	0.27	2.71	25.9	40.2	-5.2	-3.78	.0021	
7	0.00	-	-	-	-	-	.0013	

5.2 Equivalent Sand Roughness and Two Dimensional Spacing

Table 5.2 indicates the equivalent sand roughness height and equivalent two dimensional roughness density parameter that were determined by matching the experimental and predicted momentum thickness growth of the frost plates. Section 4.5 outlined the method used to determine these values.

The λ_1 values are generally much greater than the λ_3 values determined from the photographs and height measurements of the frost plates. This is to be expected since λ_1 correlates to the simple two dimensional or square rod

roughness elements which would span the entire width of the plate creating a greater overall cross sectional area to the flow. Frost Plates 3 and 4 have comparable λ_1 and λ_3 values due to their dense and distinct patterns of frost. The large, solid crystalline frost on Frost Plates 1 and 5 were matched with large equivalent two dimensional spacing parameters and had low k_s/k_f values which indicates that the crystal shape has a significant effect on the boundary layer development.

The λ_1 values included in Table 5.2 are useful in that they can be applied when modeling any of the six specific frost specimens that were tested and documented. The k_s/k_f values are indicative of the severity of the frost and are further evaluated in Section 6.4.

Table 5.2 Equivalent sand roughness height and square rod spacing for frost specimens.

Plate No.	k_s m m	k_s / k_f --	λ_1 --
1	0.586	0.78	58.5
2	0.500	1.00	31.6
3	0.875	2.27	12.9
4	0.604	1.63	16.3
5	0.214	0.61	69.0
6	0.350	1.30	32.0

5.3 Determination of Bluntness Factor for Frost

In order to determine the λ_3 values in Table 5.1 it was necessary to determine a bluntness factor for frost crystals. This was done by compiling roughness element spacing parameters and log law intercepts from references and plotting them with a semi-log scale as shown in Figure 5.22. A least squares fit was applied to the points and the resulting functions for the

log law intercept shift and spacing parameter was found to be:

$$C(\lambda_3) = 12.409 (\log \lambda_3) - 8.634 \quad \text{for } \lambda_3 < 5.6 \quad (5.1)$$

and

$$C(\lambda_3) = -12.169 (\log \lambda_3) + 9.696 \quad \text{for } \lambda_3 \geq 5.6 \quad (5.2)$$

By varying the bluntness factor term in the spacing parameter for frost it was possible to fit the experimental data for $C(\lambda_3)$ to the functions given in Equation 5.2. The best fit occurred for an $A_p/A_s = 0.90$. That is, when λ_3 was calculated using A_p/A_s in Equation 2.24 and the experimental data for $C(\lambda_3)$ were plotted against λ_3 , the points correlated reasonably well with the data in Figure 5.22.

The value of A_p/A_s for cones and spherical segments is 0.42 and that for spheres is 0.5. Upright plates facing the flow have an $A_p/A_s = 1.0$. It would be expected that the crystalline structure of frost would create a bluntness factor between that for a sphere and that for an upright plate. Therefore the value of $A_p/A_s = 0.90$ for frost seems quite reasonable.

The peak of the log law shift function shown in Figure 5.21 represents the maximum possible disruption caused by a roughness element within the boundary layer. This point will occur for a roughness element that has little or no streamlining and is shaped so that it will shed comparatively large vortices.

A scalloped roughness element with an open face against the flow would have the effect of extracting a large amount of energy from the flow resulting in an increased frictional coefficient. Frost crystals with a dense growth of ice trees and dendrites slanted into the flow would have a similar effect.

The peak shown in Figure 5.21 would then occur for a roughness element with a very large drag coefficient and have the optimum spacing of $\lambda_s = 5.6$

6.0 DISCUSSION

6.1 Wind Tunnel Flow Quality

Initial calibrations done on the wind tunnel test section indicated a 3% linear increase in velocity from Station 1 to Station 5. This favourable pressure gradient was considered to be small enough that the flow could be taken as that for the zero pressure gradient case. Calibrations done by Nituch (1972) for the smooth test section floor also indicated this slight favourable pressure gradient.

Nituch also determined that the test section maintained two dimensional flow in the law of the wall region of the velocity profile. He used geometrically identical Preston tubes to determine the transverse variation of skin friction along the test sections length. It was determined that wall shear stress on either side of the centerline would vary less than 5% of the centerline value. The skin friction variation was due to the wind tunnels settling chamber turbulence damping screens. Fluctuation along the transverse positions of the test section could be attributed to the screens having too dense of a weave, non-uniformities within the weave, and curvature of the screen when operated at high velocity.

Since Nituch's tests were done for the smooth wall case, the two-dimensionality in the flow over rough walls was determined as follows. A modified form of the momentum integral equation can be applied for convergent or divergent flows:

$$d\Theta/dx = C_f/2 + \Theta/(X_0 - x) \quad (6.1)$$

The term $\Theta/X_0 - x$ is a measure of the convergence. X_0 is the x-coordinate of a hypothetical downstream point where the converging streamlines would intersect. This hypothetical model is illustrated in Figure 6.1. The hypothetical convergence point X_0 was determined from the slope of the displacement thickness height growth along the length of the wind tunnel test section. A value of equal to double that of the maximum observed value would result in the $\Theta/X_0 - x$ term to be substantially smaller than the $C_f/2$ term. This would indicate that convergence has a negligible effect on the flow.

The indistinct crystalline structure of some of the frost specimens did not allow a straightforward method of determining the frost density. The frost specimens shown in Photographic Plates 2 and 4 did not have well defined or isolated crystals. In these cases the crystal peaks were surrounded by low lying frost developments. These areas of smaller crystalline development were judged to be of little significance and were not taken into account in calculating the λ_3 values. This determined due to the most prominent effects of the frost crystal would occur where it would extend the greatest height into the flow. The frost density values for Frost Plates 2 and 4 were calculated by the number of frost peaks in a given area.

The step change in roughness experienced by the flow as it entered the test section was considered to have a negligible effect on the determination of the skin friction using the log law as the log law region is rapidly established after the flow is disturbed by a step change in roughness. Considering the relatively small roughness element height and high Reynolds number the equilibrium flow in the near wall region would be established well ahead of the first station along the frost plate. Nituch's experiments also indicated the turbulence level for the wind tunnel was below 2%.

6.2 Practical Applications of the Bluntness Factor for Frost

The flight test data from the experiments done on the Boeing aircraft using artificial roughness could be re-evaluated in light of the bluntness factor determined for frost. The roughness elements created by the potting material used in these flight tests appear to have a conical shape. These elements would then have a bluntness factor of $A_p/A_s = 0.42$ compared to $A_p/A_s = 0.90$ for frost. The equivalent frost roughness height for a particular density of cones can be determined by equating the roughness element parameter, λ_3 , such that:

$$D/k_f (A_p/A_s)_f^{-4/3} = \lambda_3 = D/k_{\text{cone}} (A_p/A_s)_{\text{cone}}^{-4/3}$$

or

$$k_f/k_{\text{cone}} = [(A_p/A_s)_f / (A_p/A_s)_{\text{cone}}]^{-4/3}$$

and substituting in the respective bluntness factors we have for the same D values:

$$k_f = 0.362 k_{\text{cone}} \quad (6.2)$$

Equation 6.2 can be used to determine a representative frost height for the flight test data shown in Figure 2.12. In this case, the thickest cone roughness height of 1.27 mm would be equivalent to a frost thickness of 0.46 mm.

This approach could similarly be applied to the NACA 0012 airfoil performance determined by Gregory (1973) as shown in Figure 1.2. In this case, spheres were used as the roughness element with:

$$k_f = 0.457 k_{\text{sphere}} \quad (6.3)$$

such that spheres of 0.30 mm would be equivalent to frost of 0.14 mm in height.

6.3 Spacing Parameter and Law of the Wall Intercept Function

Figure 5.22 shows the law of the wall intercept as a function of the spacing parameter λ_3 . This figure is similar in shape to the relationships determined by Dvorak, Simpson, and Dirling in Figures 2.6, 2.7 and 2.8. In Figure 5.22 the maximum shift of the log law occurs for a spacing of $\lambda_3 = 5.6$. The shape of the curve in this figure is determined by drag created by cavity flow for $\lambda_3 < 5.6$ and form drag on the roughness elements for $\lambda_3 > 5.6$.

The extreme left of this figure represents a very dense spacing of the roughness elements such that a new surface is created. As the value of the spacing parameter increases, larger cavities are formed that will cause an increased degree of drag and have a greater affect on the law of the wall intercept.

For very large values of λ_3 at the extreme right of this figure the roughness elements are spaced very far apart and have a minimal effect on the law of the wall intercept. As the spacing parameter decreases the density of the roughness elements is increased causing more form drag. This increase in form drag will cause a more pronounced downward shift in the law of the wall intercept.

The coordinates for the peak of the curve in Figure 5.22 are $\lambda_3 = 5.6$ and $C[\lambda_3] = 1.92$. The maximum equivalent sand roughness height for frost or any other roughness element can be determined by applying Schlichting's (1955) formula for equivalent sand roughness for a known law of the wall intercept shift. This equation is:

$$A \log k_s/k - 3 = C[\lambda_3] \quad (6.4)$$

The maximum equivalent sand roughness height would then be:

$$k_s \leq 4.43 k \quad (6.5)$$

This maximum or peak value would correspond to conditions in the experiments done by Nikuradse where the sand particles were packed as densely as possible. This value is also less than the value determined by Dietenberger (1981) and included in Equation 2.29. It appears to be a reasonable value when compared with the equivalent sand heights for frost given in Table 5.2.

6.4 Suitability of Using Equivalent Sand Roughness Heights for Modeling Frost Roughness

Dvorak determined the equivalent square rod spacing for Nikuradse's sand roughness experiments to be $\lambda_1 = 3.17$. This value indicates that the increase in the frictional coefficient due to sand roughness is caused by drag

created in a cavity type flow. Figure 5.22 shows that the spacing parameters for all six frost specimens were greater than $\lambda_3 = 6.0$. This indicates that the drag caused by the frost was created by form drag.

In modeling frost roughness it would be beneficial to use the same drag producing mechanism as in the actual case. This implies that applying an equivalent sand roughness is not the most suitable method to effectively model the aerodynamic characteristics of frost roughness. This comparison is useful in providing a qualitative assessment of the possible profound effects of frost roughness.

The application of conical or spherical roughness elements with varying heights and spacing and with a constant and measurable bluntness factor would be more effective when modeling frost roughness on airfoils.

6.5 Suggestions for Further Study

The six samples of frost that were tested have provided a basis for frost research by may not be representative of the total family of frost crystals that may form on airfoil surfaces. To expand the applicability of this research, cataloging of as many crystal types are required. Ideally this would require photographs of frost on the wings of various aircraft to determine crystal size and spacing and utilizing the frost measuring device to determine height. This data base would indicate average and maximum frost spacing parameters that would be applied to the data in Figure 5.22. Specifically it would determine maximum and average parameters of law of the wall shift that would be useful in modeling and evaluating the boundary layer growth.

It would be expected that the good results acquired from the very large frost plates (1.83 m X .76 m) could also be taken from smaller specimens that are easier to acquire and that would require less total resources and a smaller wind tunnel. Additional points applied to Figure 5.22 would allow a more precise value of A_p/A_s for frost to be determined. The six frost specimens could also be retested after removing a certain percentage of the

crystals, thus increasing the λ value and supplying more data points for the figure. It is not known if natural frost would nucleate in the same modified pattern and the aforementioned catalog of frost would be required to validate this approach.

The simple and effective procedure for preserving frost crystals could be used to preserve the nocturnal frost growth on an entire test aircraft. Test flights similar to those done by Boeing could be used for evaluating the degree of performance degradation.

The results from the six documented frost specimens can be applied to wind tunnel tests of airfoils and to computer models of aircraft performance. Section 6.2 outlined how equivalent frost height can be reproduced using a variety of geometrically different roughness elements that would not require actual frost crystals to be collected and preserved on the airfoil test section. It also alleviates the problem of scaling for smaller models of wing sections.

The functions derived from Figure 5.22 relating shift in the log law provides the necessary tool for computer models to evaluate airfoil and aircraft performance. New airfoil designs can be evaluated by measuring their susceptibility to surface contamination. Expected degradation of performance can be determined providing guidelines for modified rotation rates, take-off speed and distance and climb profile. Specifically, such a model would create an analogous performance decrease between a certain type of frost and an equivalent increase in take-off weight or decrease in the available thrust.

Evaluation of partial clearing of frost from wings can also be made with these computer models. In the interest of flight safety, these models can be incorporated into flight simulators used in training. A more effective computer model could also be applied to accident investigation. Input from post-crash measurements of the frost on the aircraft and the flight data recorder would reveal if wing contamination was the primary cause of the accident.

Further investigation is required in the prevention of frost growth. This can be done by denying nucleation sites on the surface or by affecting a change to the heat transfer from the wing to space.

7.0 CONCLUSIONS

This thesis has evaluated the aerodynamic characteristics of preserved frost crystals in a turbulent flow. The results from the wind tunnel tests of six frost specimens have indicated that frost creates a bluntness factor nearly that equivalent to a vertical plate having the same dimensions as the frost crystal. Frost height and spacing have significant effects on the boundary layer growth. The coefficient of friction can be doubled for a surface contaminated with less than half a millimeter of widely spaced nocturnal frost crystals.

Other conclusions drawn from experimental results include:

- Frost samples can be readily acquired and effectively preserved for wind tunnel testing.
- Effective modeling of boundary layer growth with roughness elements can be realized using computer programs.
- A three dimensional spacing parameter is suitable and valid for determining a function for log law shift and can be applied to a large variety of roughness element types.
- Comparison of frost roughness to an equivalent sand roughness is useful for a qualitative analysis of the effects of frost in a boundary layer.
- An equivalent frost roughness height can be determined for various geometries of roughness elements such as spheres, cones, and vertical plates.

- Indirect methods of determining skin friction can be accomplished using law of the wall, momentum integral equations and computer codes utilizing entrainment equations and friction law.

- Use of the functions relating shift in the log law to a three dimensional spacing parameter will allow computation of performance of airfoils contaminated with frost.

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APPENDIX A**FIGURES**

Figure 1.1 Airflow over a smooth and rough airfoil.
(Reproduced from Luers, 1983)

Figure 1.2 Lift and drag curves for a NACA 0012 Airfoil with surface roughness. Solid line is taken from a clean wing and dashed line represents a wing contaminated with spheres $k=0.3$ mm and 295 spheres/in². (Data from Gregory and O'Reilly, 1973)

Figure 2.1 Defect Law showing $(u - U_e)/u_\tau$ as a function of y/δ .
(Reproduced from Clauser, 1954)

Figure 2.2 Law of the wall.
(Reproduced from White, 1974)

Figure 2.3 Downward shift of the law of the wall intercept due to surface roughness.
(Reproduced from White, 1974)

No	item	dimensions	D [cm]	d [cm]	k [cm]	k_s [cm]	photographs	
1	spheres		4	0.41	0.41	0.093		
2			2	0.41	0.41	0.346		
3			1	0.41	0.41	1.26		
4			0.6	0.41	0.41	1.56		
5			denser array		0.41	0.41		0.257
6			1	0.21	0.21	0.172		
7			0.5	0.21	0.21	0.759		
8	spherical segments		4	0.8	0.26	0.031		
9			3	0.8	0.26	0.049		
10			2	0.8	0.26	0.149		
11			denser array		0.8	0.26		0.365
12	cones		4	0.8	0.375	0.059		
13			3	0.8	0.375	0.164		
14			2	0.8	0.375	0.374		
15	"short" angles		4	0.8	0.30	0.291		
16			3	0.8	0.30	0.618		
17			2	0.8	0.30	1.47		

Plate No.	d (cm)	D (cm)	l (cm)	k (cm)	k' (cm)	b (cm)	Schl. k_p/k	Corr. k_p/l
Spheres								
XII	0.41	4	4	0.41	—	3.99	0.227	0.120
III	0.41	2	2	0.41	—	3.99	0.838	0.410
I	0.41	1	1	0.41	—	3.96	3.07	2.43
II	0.41	0.6	0.6	0.41	—	3.88	3.81	2.59
V	0.41	0.41	0.36	0.41	—	3.68	0.626	0.378
VI	0.21	1	1	0.21	—	3.99	0.819	0.430
IV	0.21	0.5	0.5	0.21	—	3.97	3.61	2.47
Spherical segments								
XIII	0.8	4	4	0.26	—	3.99	0.118	0.018
XIV	0.8	3	3	0.26	—	3.99	0.186	0.034
XV	0.8	2	2	0.26	—	3.98	0.571	0.278
XIX	0.8	0.8	0.69	0.26	—	3.85	1.40	0.953
Cones								
XXIII	0.8	4	4	0.375	0.425	3.99	0.159	0.046
XXIV	0.8	3	3	0.375	0.425	3.98	0.437	0.122
XXV	0.8	2	2	0.375	0.425	3.95	0.996	0.471

Figure 2.4 Equivalent sand roughness heights for regular roughness patterns and corrected values.
(Reproduced from Schlichting, 1955 and Coleman et al, 1984)

Figure 2.5 Effect of roughness height on the law of the wall intercept. (Reproduced from Dvorak, 1969)

Figure 2.6 Effect of 2 dimensional roughness density on law of the wall intercept. (Reproduced from Dvorak, 1969)

Figure 2.7 Effect of roughness density ($\lambda_k = \lambda_2$) on the law of the wall intercept. (Reproduced from Simpson, 1972)

$$\lambda_3 = (D/k) (A_p/A_s)^{-4/3}$$

Figure 2.8 Effect of roughness element spacing and shape on equivalent sand roughness. (Reproduced from Dirling, 1973)

Figure 2.9 Clauser Plot for determining turbulent skin friction.
(Reproduced from Clauser 1953)

Figure 2.10 Comparison of observed and predicted forced convection frost roughness.
(Reproduced from Chen and Rohsenow, 1964)

Figure 4 - Stall speed increase - Flaps 1.

Figure 5 - Stall speed increase - Flaps 15

Figure 5 - Stall speed increase - Flaps 40

Figure 2.11 Results from Boeing flight tests with artificially roughened wings. (Reproduced from Hill, 1982)

Figure 3.1 Traversing station locations along wind tunnel test section.

Figure 3.2 SETRA pressure transducer calibration.

Figure 3.3 Pitot tube dimensions.

Figure 4.1 Pitot tube seating and flexure during initial steps.

Figure 4.2 Sample of pressure transducer output during initial three steps.

Figure 4.3 Determining frictional coefficient from slope of Clauser plot for Plate 4.

Figure 4.4 Matching momentum thickness growth by varying λ_1 with $k = k_f$ Frost Plate 4

Figure 4.5 Matching momentum thickness growth by varying k_s for a given k_f Plate 4 K_s values determined for $\lambda_f=3.17$

Figure 5.1

Frost Plate 1
 $U_e = 51$ m/s

Boundary layer profile and Clauser plot
 Avg $C_f = 0.0046$

Figure 5.2 Frost Plate 2 Boundary layer profile and Clauser plot
 $U_e = 51 \text{ m/s}$
 Avg $C_f = 0.0043$

Figure 5.3 Frost Plate 3 Boundary layer profile and Clauser plot
 $U_e = 51 \text{ m/s}$ Avg $C_f = 0.0052$

Figure 5.4

Frost Plate 4
 $U_e = 51$ m/s

Boundary layer profile and Clauser plot
 Avg $C_f = 0.0049$

Figure 5.5 Frost Plate 5 Boundary layer profile and Clauser plot
 $U_e = 51$ m/s Avg $C_f = 0.0036$

Figure 5.6

Frost Plate 6
 $U_e = 51 \text{ m/s}$

Boundary layer profile and Clauser plot
 Avg $C_f = 0.0042$

Figure 5.7 Smooth Plate 7 Boundary layer profile and Clauser plot
 $U_e = 51$ m/s Avg $C_f = 0.0027$

Figure 5.8 Frost Plate 1 Experimental and predicted results for C_f , θ , H , and δ .
Dashed line represents Dvorak's prediction for $k_2 = .586 \text{ mm}$

Figure 5.9 Frost Plate 2 Experimental and predicted results for C_f , θ , H , and δ .
Dashed line represents Dvorak's prediction for $k_s = 500$ mm

Figure 5.10 Frost Plate 3 Experimental and predicted results for C_f , θ , H , and δ .
Dashed line represents Dvorak's prediction for $k_s = 0.875 \text{ mm}$

Figure 5.11 Frost Plate 4 Experimental and predicted results for C_f , θ , H , and δ .
Dashed line represents Dvorak's prediction for $k_s = 604$ mm

Figure 5.12 Frost Plate 5 Experimental and predicted results for C_f , θ , H , and δ .
Dashed line represents Dvorak's prediction for $k_s = 214$ mm

Figure 5.13 Frost Plate 6 Experimental and predicted results for C_f , θ , H , and δ .
 Dashed line represents Dvorak's prediction for $k_s = 350$ mm

Figure 5.14 Smooth Plate 7 Experimental and predicted results for C_f , θ , H , and δ .
Dashed line represents Dvorak's prediction for $k = 0.0$ mm

Figure 5.15 Frost Plate 1 Law of the wall velocity distribution

$\Delta B = -6.4$ $C[\lambda_3] = 5.18$

Dashed line represents the distribution for a smooth plate $A=5.75$ and $B=5.5$

Figure 5.15 Frost Plate 1 Law of the wall velocity distribution

$$\Delta B = -6.4 \quad C[\lambda_3] = 5.18$$

Dashed line represents the distribution for a smooth plate $A=5.75$ and $B=5.5$

Figure 5.16 Frost Plate 2 Law of the wall velocity distribution
 $\Delta B = -5.5$ $C[\lambda_3] = 5.01$

Dashed line represents the distribution for a smooth plate $A=5.75$ and $B=5.5$

Figure 5.17 Frost Plate 3 Law of the wall velocity distribution
 $\Delta B = -8.3$ $C[\lambda_3] = 1.81$

Dashed line represents the distribution for a smooth plate $A=5.75$ and $B=5.5$

Figure 5.18 Frost Plate 4 Law of the wall velocity distribution

$$\Delta B = -6.9 \quad C[\lambda_3] = 3.04$$

Dashed line represents the distribution for a smooth plate $A=5.75$ and $B=5.5$

Figure 5.19 Frost Plate 5 Law of the wall velocity distribution

$$\Delta B = -3.1 \quad C[\lambda_3] = 6.33$$

Dashed line represents the distribution for a smooth plate $A=5.75$ and $B=5.5$

Figure 5.20 Frost Plate 6 Law of the wall velocity distribution
 $\Delta B = -5.2$ $C[\lambda_3] = 3.78$

Dashed line represents the distribution for a smooth plate $A=5.75$ and $B=5.5$

Figure 5.21 Smooth Plate 7 Law of the wall velocity distribution
 Dashed line represents the distribution for a smooth plate $A=5.75$ and $B=5.5$

Figure 5.22 Law of the wall intercept as a function of roughness element spacing parameter $[\lambda_3 = D/k(A_p/A_s)^{-4/3}]$

Figure 6.1 Measurement of convergence within a wind tunnel test section.

APPENDIX B**PHOTOGRAPHIC PLATES**

Plate 2.1

1 cm thick frost collected in the Colorado Rockies.
(Photo by Borys, 1987)

Plate 3.1 Traversing gear with depth dial indicator.

Plate 3.2 Wind tunnel test set-up with data acquisition system.

Plate 3.3 Short and long stemmed pitot tubes.

5 cm

Plate 4.1 Natural frost crystals preserved using formvar and ethylene dichloride.

Plate 4.2 Frost height measuring device.

Plate 4.3 Pitot tube placement at start of test run.

5 cm

Plate 5.1 Frost Plate 1 $k_f = 0.75 \text{ mm}$ $1/D^2 = 1.91 \text{ crystals/cm}^2$

5 cm

Plate 5.2 Frost Plate 2 $k_f = 0.50 \text{ mm}$ $1/D^2 = 5.11 \text{ crystals/cm}^2$

5 cm

Plate 5.3 Frost Plate 3 $k_f = 0.385 \text{ mm}$ $1/D^2 = 3.80 \text{ crystals/cm}^2$

5 cm

Plate 5.4 Frost Plate 4 $k_f = 0.37 \text{ mm}$ $1/D^2 = 3.17 \text{ crystals/cm}^2$

Plate 5.5 Frost Plate 5 $k_f = 0.35 \text{ mm}$ $1/D^2 = 1.12 \text{ crystals/cm}^2$

Plate 5.6 Frost Plate 6 $k_f = 0.27 \text{ mm}$ $1/D^2 = 2.71 \text{ crystals/cm}^2$

APPENDIX C**COMPUTER SOURCE CODES AND SAMPLE OUTPUT**

BLM.BAS	BASIC program for data acquisition and stepping the traversing gear motor.
DATARED.FOR	FORTTRAN program for reducing pressure transducer output to determine the velocity profile and Reynolds number.
PROFILE.FOR	FORTTRAN program that fits a seventh order polynomial through sections of the velocity profile to be integrated to determine momentum thickness, displacement thickness, and shape factor.
BLP.FOR	FORTTRAN program that calculates the development of a two dimensional turbulent boundary layer over rough surfaces using functions from Dvorak(1969).

```

10  *
20  *
30  *
40  *   Program Boundary Layer Measurement
50  *
60  *   This program is used with motorized traversing gear and
the
70  *   Taurus data acquisition system.
90  *   The output consists of all relevant experimental
92  *   data and a table of number of points, distance from
wall, and
94  *   the transducer readings from the reference and
traversing pitot
96  *   tubes (given in volts).
98  *
105 *
110   DIM  AIN2(2000) , CP(400), AIN1(2000), TDIST(400),
REF(400)
120   *
123   CLS
124   *
125  * ++++++ INITIAL DATA INPUT FOR TEST RUN

127   PRINT  " "
130  PRINT  "                                REPOSITION THE PITOT TUBE
"
140  PRINT  " "
150   GOTO 1410
160   *
165   CLS
170   INPUT "ENTER DATE OF TEST RUN      ", TDATE$
180   PRINT
190  * INPUT "ENTER BAROMETRIC PRESSURE   in KPa      ", BP
200   PRINT
210   INPUT "ENTER DATA FILE NAME     ", FAME$
220   PRINT
230  INPUT "ENTER INITIAL STEP SIZE FOR MOTOR   in Inches " ,
DISP
240   PRINT
250  INPUT "ENTER TOTAL TRAVERSING DISTANCE   in Inches ", DIST

260   PRINT
270  INPUT "ENTER DIRECTION :UP OR DOWN (usually up)  "
,DIRECT$
280   PRINT
290  * INPUT "ENTER SAMPLING TIME (less than 60 sec)  " , JJ%
300  * PRINT      °SAMPLING TIME SET AT 30 SEC
305  JJ%=30
310  * INPUT "ENTER WAITING PERIOD (less than 60 sec)  " , WSEC
320  * PRINT      °WAITING PERIOD SET AT 10 SEC
325  WSEC=10
322   V%=1.0   °STEP SIZE INCREASED BY V IF AVG OF PTS ARE GT
95%
324   DISPl=DISP °OR INCREASED BY INITIAL DISP FOR EACH TIME

```

[illegible]

```

725      PRINT , "
-----"
726      °
730      ° ++++++ INITIALIZE VARIABLES
740      AIS="AI"
750      TINP$ = "INP" : TOUT$ = "OUT"
760      ASUM = 0!
770      ASUM1=0!
780      TDIST(0)=(-1! * DISP)
790      Y%=0
795      NKK%=0
800      NOER% = 0
805      °
810      °+++++ LOAD AND INITIALIZE TSOFT

820      DEF SEG = &H0
830      TAURUS = 506 : INZ$ = "INZ"
840      CALL TAURUS (INZ$,ERRCOD%)
850      IF ERRCOD%$0 THEN GOSUB 2150 :GOTO 840 ~
855      °
860      °+++++ MAIN PROGRAM
870      KK%=1
880      GOTO 920
890      KK%=KK%+1      °START OF THE LOOP
900      GOSUB 1500      ° STEPS THE MOTOR
910      GOSUB 1730      ° WAITS BEFORE TAKING DATA AND CHECKS STEP
SIZE
920      TIMES$ = "00:00:00"
930      °
940      II% = 0
950      II% = II% + 1
960      °
970      ° ++++++ SAMPLING TIME JJ%
990      °
1020      IF (VAL(RIGHT$(TIMES$,2)) + JJ%) THEN GOTO 1180 ELSE
GOTO 1080
1080      °
1090      °+++++ READING ANALOG INPUTS 1 AND 2

1100      CALL TAURUS (TINP$,AIS,LAIN2%,AIN2(II%),ERRCOD%)
1110      IF ERRCOD% $ 0 THEN GOSUB 2150
1120      ASUM = ASUM + AIN2(II%)
1130      CALL TAURUS (TINP$,AIS,LAIN1%,AIN1(II%),ERRCOD%)
1140      IF ERRCOD% $ 0 THEN GOSUB 2150
1150      ASUM1=ASUM1+AIN1(II%)
1160      GOTO 950
1170      °
1180      °+++++ ARCHIVING THE DATA
1190      °
1200      °
1210      ASUM = ASUM/(II%-1)
1220      ASUM1=ASUM1/(II%-1)
1230      J%=KK%-1

```

```

1240   TDIST(KK%)=TDIST(J%)+DISP
1250   REF(KK%)=ASUM1
1260   CP(KK%)=ASUM
1270   PRINT, USING "   ####.#####";
KK%,TDIST(KK%),CP(KK%),REF(KK%)
1280   °
1290   IF (TDIST(KK%) $ DIST) THEN GOTO 890
1300   GOSUB 1890 ° PRINTING FIRST PART OF DATA FILE
1310   OPEN FAME$ FOR APPEND AS #3
1320   FOR K%=1 TO KK%
1330   PRINT#3, USING "   ####.#####";
K%,TDIST(K%),CP(K%),REF(K%)
1340   NEXT K%
1350   CLOSE 3
1355   PRINT " "
1360   PRINT "TO RUN THE PROGRAM AGAIN ,TYPE   RUN "
1362   PRINT " "
1364   PRINT " "
1370   GOTO 2210
1380 °
1390 ° ++++++ SUBROUTINE FOR REPOSITIONING
PITOT TUBE
1400 °
1410   PRINT " REPOSITIONING PITOT TUBE: "
1420   PRINT " hit return when finished "
1425   PRINT " "
1430   INPUT " DISTANCE TO BE MOVED           ",DISP
1440   PRINT
1445   IF DISP=0 THEN GOTO 160
1450   INPUT " DIRECTION OF MOVEMENT UP (up) OR DOWN (down)
",DIRECT$
1460   PRINT
1465   PRINT " "
1470 °
1480   GOSUB 1500
1490   GOTO 1410
1500 °
1505 ° ++++++ SUBROUTINE FOR STEPPING
THE MOTOR
1510   HDISP=DISP/2
1520   A%=CINT(HDISP*4184)
1530   IF DIRECT$="UP" THEN GOSUB 1560
1540   IF DIRECT$="DOWN" THEN GOSUB 1640
1550   RETURN
1560   FOR B%=1 TO 2
1570   FOR C%=1 TO A%
1580   OUT 888,12
1590   OUT 888, 4
1600   NEXT C%
1610   OUT 888,0
1620   NEXT B%
1630   RETURN
1640   FOR B%=1 TO 2
1650   FOR C%=1 TO A%

```

```

1660 OUT 888 , 6
1670 OUT 888 , 4
1680 NEXT C%
1690 OUT 888 , 0
1700 NEXT B%
1710 RETURN
1714 °
1715 ° ++++++ SUBROUTINE FOR PAUSE AND INC STEP SIZE

1720 °
1730   TIMES$="00:00:00"
1740 IF (VAL(RIGHT$(TIMES$,2))=0) THEN GOTO 1750 °OR PRINT WAIT

1750 IF (VAL(RIGHT$(TIMES$,2)) $ WSEC) THEN GOTO 1740
1752 °   START OF MOD  3 OCT 87
1756 °   FOR A STEP INC OF 1.136  WILL RESULT IN 100 POINTS
IN 3 in AT .001
1758 GOTO 1855
1759 °   END OF MOD    3 OCT 87
1760 IF KK% $ 16 THEN GOTO 1870
1762 NKK%=NKK%+1
1763 IF NKK% $ 16 THEN GOTO 1870
1764 NKK%=0
1770 IF Y% + 10 THEN GOTO 1870 ° MAX STEP SIZE IS 10x
INITIAL STEP SIZE
1780 ZSUM=0
1790 FOR W% = 1 TO 8
1800 X%=KK%-W%
1810 ZSUM=ZSUM+AIN2(X%)
1820 NEXT W%
1830 ZSUM=ZSUM/5
1840 AVG5=(ZSUM/AIN2(KK%))
1845 IF AVG5 $ 0.99 AND AVG5 + 1.01 THEN GOTO 1870
1850 Y%=Y%+1
1855 ° DISP USED TO BE 2      OCT 3 87
1860 DISP=DISP*1.050000 ° STEP SIZE INCREASED BY FACTOR OF
2
1870 °
1880 RETURN
1885 °
1886 ° ++++++ ENTERING FINAL DATA VALUES
1890 °
1900 INPUT "ENTER FINAL TOTAL TEMPERATURE " ,T2
1910 PRINT
1925 INPUT "ENTER FINAL MANOMETER READING " ,M2
1926 PRINT
1927 PRINT " "
1928 PRINT " TURN DOWN WIND TUNNEL"
1929 PRINT " "
1930 PRINT " "
1931 INPUT "ENTER FINAL BL TRANSDUCER VOLTAGE : " ,VF
1932 PRINT
1933 INPUT "ENTER FINAL REF TRANSDUCER VOLTAGE : " ,VREFF

```



```

1934 PRINT
1935 ° ++++++ SUBROUTINE FOR PRINTING INITIAL
DATA OUT
1940 OPEN FAMES$ FOR APPEND AS #2
1950 PRINT#2, "0.0" ***** BOUNDARY LAYER MEASUREMENTS *****
1960 PRINT#2, "1.0" , TDATE$, " TEST DATE "
1970 PRINT#2, "2.0" , BP, " BAROMETRIC PRESSURE "
1980 PRINT#2, "3.0" , T1, " INITIAL TOTAL TEMP "
1990 PRINT#2, "4.0" , T2, " FINAL TOTAL TEMP "
2000 PRINT#2, "5.0" , M1, " INITIAL MANOMETER READING"

2010 PRINT#2, "6.0" , M2, " FINAL MANOMETER READING"
2020 PRINT#2, "7.0" , JJ%, " SAMPLING TIME FOR EACH
STEP"
2030 PRINT#2, "8.0" , II%, " NUMBER OF SAMPLES TAKEN"
2040 PRINT#2, "9.0" , WSEC, " WAITING PERIOD BETWEEN
STEPS"
2050 PRINT#2, "10.0" , DIST, " TOTAL TRAVERSING
DISTANCE"
2060 PRINT#2, "11.0" , KK%, " NUMBER OF POINTS ON
PROFILE"
2070 PRINT#2, "12.0" , V1, " INITIAL REF VOLTAGE FROM
PRES TD"
2080 PRINT#2, "13.0" , V2, " INITIAL BL VOLTAGE FROM
PRES TD"
2082 PRINT#2, "14.0" , VREFF, " FINAL REF VOLTAGE
FROM PRES TD"
2084 PRINT#2, "15.0" , VF, " FINAL BL VOLTAGE
FROM PRES TD"
2090 PRINT#2, " "
2092 PRINT#2, "19" STEP NO. DIST Q
Qref"
2094 PRINT#2, "20
----- "

2100 CLOSE 2
2110 RETURN
2120 °
2130 °
2140 ° ++++++ ERROR SUBROUTINE
2150 NOER = NOER + 1 : IF NOER = 9999 THEN NOER = 9999
2160 PRINT " ERROR FROM TAURUS BOARD : ERRCODE NO.OF
ERROR "
2170 PRINT "*****ERROR: ";
2180 PRINT USING "#####"; ERRCOD%; NOER
2190 SOUND 100,1
2200 RETURN
2210 STOP

```

0.0 ***** BOUNDARY LAYER MEASUREMENTS *****
1.0 080288 TEST DATE 111
2.0 104 BAROMETRIC PRESSURE
3.0 88 INITIAL TOTAL TEMP
4.0 94 FINAL TOTAL TEMP
5.0 139 INITIAL MANOMETER READING
6.0 139 FINAL MANOMETER READING
7.0 30 SAMPLING TIME FOR EACH STEP
8.0 312 NUMBER OF SAMPLES TAKEN
9.0 10 WAITING PERIOD BETWEEN STEPS
10.0 2.4 TOTAL TRAVERSING DISTANCE
11.0 90 NUMBER OF POINTS ON PROFILE
12.0 .0645 INITIAL REF VOLTAGE FROM PRES TD
13.0 -.0279 INITIAL BL VOLTAGE FROM PRES TD
14.0 .0661 FINAL REF VOLTAGE FROM PRES TD
15.0 -.0269 FINAL BL VOLTAGE FROM PRES TD

19	STEP NO.	DIST	Q	Qref
20	-----	-----	-----	-----
	1.000000	0.000000	0.074726	1.055312
	2.000000	0.000945	0.135765	1.070977
	3.000000	0.001937	0.136407	1.072338
	4.000000	0.002979	0.136663	1.069805
	5.000000	0.004073	0.136542	1.070268
	6.000000	0.005222	0.136616	1.070740
	7.000000	0.006428	0.136652	1.070804
	8.000000	0.007694	0.137865	1.070715
	9.000000	0.009024	0.150815	1.070174
	10.000000	0.010420	0.162968	1.070310
	11.000000	0.011886	0.171942	1.069628
	12.000000	0.013425	0.180476	1.069875
	13.000000	0.015042	0.188647	1.067758
	14.000000	0.016739	0.194184	1.068699
	15.000000	0.018521	0.203222	1.065177
	95.000000	1.835718	1.101424	1.046677
	96.000000	1.928448	1.102233	1.047487
	97.000000	2.025816	1.100862	1.043796
	98.000000	2.128051	1.103366	1.049589
	99.000000	2.235399	1.103817	1.049270
	100.000000	2.348114	1.091031	1.040999
	101.000000	2.466464	1.103059	1.047351

Table C.1 Sample output from data acquisition program BLM.BAS .
Q and Q_{ref} are the transducer voltages and distance is
given in inches above the wind tunnel floor.

```

C
C
C   THIS PROGRAM ACCEPTS THE OUTPUT FROM THE DATA ACQUISITION
C   PROGRAM BLM.BAS AND DETERMINES THE BOUNDARY LAYER VELOCITY
C   PROFILE VALUES, REYNOLDS NUMBER, AND MOMENTUM AND
DISPLACEMENT
C   THICKNESS AT THE GIVEN STATION.  OUTPUT ALSO TAKES THE FORM
C
C   FOR PLOTTING OUT THE PROFILES ON GRAPHS
C
C
C
C
C
C   PROGRAM DATARED
C   DIMENSION STEP(200),DIST(200),V(200),VREF(200),VV(200)
C   DIMENSION REYLG(200)
C   REAL M1,M2,O
C   INTEGER JJ,II,KK
C   PITOT TUBE HEIGHT IN mm
C   PITOTH=0.480
C   HEIGHT OF FLAT PITOT TUBE =PITOTH    IN MM
C   OPEN(UNIT=1,FILE=' ',STATUS='OLD')
C   OPEN(UNIT=3,FILE=' ',STATUS='NEW')
C   ++++++ READS IN THE RAW DATA
FROM 'BLM.BAS'
  READ(1,*) O
  READ(1,*) O ,DATE
  READ(1,*) O ,BP
  READ(1,*) O ,T1
  READ(1,*) O ,T2
  READ(1,*) O ,M1
  READ(1,*) O , M2
  READ(1,*) O, BJJ
  READ(1,*) O, BII
  READ(1,*) O, BWSEC
  READ(1,*) O, BDIST
  READ(1,*) O, BKK
  READ(1,*) O, VOLT2
  READ(1,*) O, VOLT1
  READ(1,*) O, VOLT2F
  READ(1,*) O, VOLT1F
  READ(1,*)
  READ(1,*) O
  READ(1,*) O
  VAVG=0.0
  N=INT(BKK)
C
C
C
C+++++ READS IN THE DISTANCE AND
TRANSducer VOLTAGE
C
  DO 200, I=1,N

```

```

      READ(1,*) STEP(I),DIST(I),V(I),VREF(I)
C+++++ CORRECTION DUE TO INITIAL AND
FINAL ZERO PRES VOLTAGE
      V1=VOLT1+(VOLT1F-VOLT1)*I/N
      V2=VOLT2+(VOLT2F-VOLT2)*I/N
C+++++ PRESSURE TRANSDUCER
CALIBRATION 1 Pa=1371 mV
      P=1.371*(V(I) - V1)*1000
      P=ABS(P)
C+++++ PRESSURE TRANSDUCER
CALIBRATION
      PREF=(1.375*(VREF(I)-V2)*1000)
      PREF=ABS(PREF)
      VREF(I)=PREF
      V(I)=P
      DIST(I)=DIST(I)*25.4
200  CONTINUE
      DO 201 I=1,18
        WRITE(*,*) I,V(I),VREF(I)
201  CONTINUE
      WRITE(*,*) °ENTER STEP WHERE PITOT TUBE LEAVES THE SURFACE°

      READ(*,*) NBEGIN
      N4=N-NBEGIN
      WRITE(3,901)
      WRITE(3,*) N4
      DISTX=DIST(NBEGIN)
      DO 230 I=1,N4
        DIST(I)=DIST(I+NBEGIN-1)-DISTX +PITOTH/2
        IF ((DIST(I)/PITOTH).GE.1) GOTO 205
C+++++ PITOT TUBE CORRECTION
C      TAKEN FROM SJOLANDER
      DELTA=PITOTH*(0.276 * ( LOG10(ABS(DIST(I)/PITOTH)) ))
      DIST(I)=DIST(I)+DELTA
205      VAVG=VAVG+VREF(I)
      V(I)=V(I+NBEGIN-1)
      VREF(I)=VREF(I+NBEGIN-1)
230  CONTINUE
      N=N4
C +++++ THE LAST 15 PITOT TUBE MEASUREMENTS OUTSIDE
C +++++ THE BOUNDARY LAYER ARE AVERAGED
      NN=N-15
      AV=0
      AVREF=0
      DO 300 I=NN , N-1
        AV=AV+V(I)
        AVREF=AVREF+VREF(I)
300  CONTINUE
      VVV=AV/15
      VVREF=AVREF/15
      VAVG=VAVG/(N-1)
      THETA=0
      DELTAS=0

```

```

      DO 400 I=1,N
C+++++ CALCULATES FREESTREAM VEL AND
LOG OF Rey NO.
C+++++
C      V IS BL PRESSURE MEASUREMENT
C      VREF IS PC1-PC2
C      VVV IS AVG 15 MEASUREMENTS OUTSIDE BL
C      VVREF IS AVG 15 MEASUREMENTS OF LAST 15 PC1 PC2 VALUES
C      VV IS U/UE
      VV(I)=SQRT(ABS(V(I)/VREF(I)))*SQRT(ABS(VVREF/VVV))
C      TEMP FOR EACH VEL MEASUREMENT
      T=T1+((T1+T2)*I/N)
      T=(T-32)/1.8
      VISC=((0.009157*T)+1.319)/100000
      TAVG=((T1+T2)/2 - 32)/1.8
      ROE=BP/(.287*(TAVG+273))
      VAVG=SQRT(ABS(VVREF*2/ROE/.91))
      REYLG(I)=LOG10(ABS(DIST(I)/1000*VAVG/VISC))
400  CONTINUE
C+++++ DETERMINING THETA, DELTASTAR
AND H FROM EXPT DATA
      VV(0)=0
      THETA=0
      DELTAS=0
      DIST(0)=0
      DO 500 I=1,N-1
        V4=((VV(I)+VV(I-1))/2)
        THETA=THETA+((V4*(1-V4))*(DIST(I)-DIST(I-1)))
        DELTAS=DELTAS+ ((1-V4)*(DIST(I)-DIST(I-1)))
500  CONTINUE
      H1=DELTAS/THETA
      WRITE(3,*) VAVG, ° m/s AVERAGE VELOCITY°
      WRITE(3,*) THETA, ° mm THETA°
      WRITE(3,*) DELTAS, ° mm DELTA STAR°
      WRITE(3,*) H1 , ° SHAPE FACTOR H°
      DO 601 I=1,N
        WRITE(3,900) I,DIST(I),V(I),VREF(I),VV(I),REYLG(I)
601  CONTINUE
899  FORMAT(G12.6)
900
FORMAT(3X,I3,3X,G12.6,3X,G12.6,3X,G12.6,3X,G12.6,3X,G12.6)
901  FORMAT('1°',2X,'STEP°',5X,'DIST°',11X,'V °',13X,'VREF°',10X,'
U/UE °',
* 9X,'LOG REY°')
STOP
END

```

1	STEP	DIST	P(b1)	Pc1-Pc2)	U/Ue	LOG REY
		82	NO. OF POINTS			115
		49.734620	m/s	AVERAGE VELOCITY		
		1.839523	mm	THETA		
		2.862262	mm	DELTA STAR		
		1.555981	SHAPE FACTOR	H		
	1	.211793	223.331	1365.24	.378587	2.81435
	2	.253179	240.773	1364.48	.393202	2.88884
	3	.295712	257.140	1364.64	.406323	2.95328
	4	.339588	269.222	1363.69	.415904	3.01038
	5	.384947	280.711	1364.00	.424637	3.06186
	6	.431977	291.711	1361.11	.433337	3.10898
	7	.480764	299.160	1362.36	.438633	3.15253
	8	.529006	311.328	1357.56	.448256	3.19115
	9	.576529	322.318	1361.33	.455467	3.22563
	10	.626415	331.623	1357.17	.462701	3.25880
	11	.678815	335.738	1339.11	.468693	3.29084
	12	.733831	342.502	1333.17	.474444	3.32186
	13	.791591	354.684	1331.85	.483047	3.35196
	14	.852246	362.582	1333.25	.488140	3.38123
	15	.915949	374.164	1333.06	.495909	3.40976
	16	.982802	385.140	1332.38	.503258	3.43760
	17	1.05303	395.231	1333.22	.509648	3.46483
	18	1.12674	404.873	1329.93	.516466	3.49150
	19	1.20416	416.875	1333.33	.523396	3.51765
	20	1.28544	426.409	1329.48	.530151	3.54333
	78	28.4983	1525.33	1334.56	1.00071	4.75622
	79	29.9443	1520.61	1334.96	.999014	4.77575
	80	31.4626	1526.07	1331.71	1.00202	4.79527
	81	33.0568	1520.66	1334.22	.999306	4.81478
	82	34.7307	1524.35	1333.91	1.00063	4.83429

Table C.2 Sample reduced data from program DATA.RED showing y , u/U_e , and $\log Re_y$

C
C
C
C
C
C
C

PROGRAM FOR VELOCITY PROFILE

```

PROGRAM PROFILE
INTEGER FLAG
DIMENSION X(20),Y(20,1),B(20,20),VV(300),DIST(200)
DIMENSION VV3(300),VV2(300),DIST2(300),COEF(20)
OPEN(UNIT=1,FILE=' ',STATUS='OLD')
OPEN(UNIT=3,FILE=' ',STATUS='NEW')
FLAG=1
J=1
NCHECK=0
C WRITE(*,*) 'DEGREE OF POLYNOMIAL      ===== 7      OK '
C READ(*,*) M
M=7
WRITE(*,*) 'ENTER NUMBER OF POINTS TO BE ENTERED'
READ(*,*) NUM
C NUM=15
      GOTO 889
888 Y(1,J)=0.00000
      X(1)=0.00000
      WRITE(*,*) Y(1,J),X(1)
      DO 903 I=2,NUM
C WRITE(*,*) 'ENTER X AND Y COORD (dist and U/Ue)'
C READ(*,*) X(I), Y(I,J)
      Y(I,J)=VV(I-1)
      X(I)=DIST(I-1)
      WRITE (*,*) Y(I,J),X(I), '          ',I
C . X(I)=X(I)/10
903 CONTINUE
      N=NUM
      CALL LSTSQR(X,Y,B,N,M,FLAG,MPI)
C ++++++ ARRAY B CONTAINS ALL THE
COEFTS
889 IF (FLAG.EQ.0) GOTO 890
      READ(1,*)O
      READ(1,*)NO
      READ(1,*)VVAVG
      READ(1,*)THETA2
      READ(1,*)DELTAS2
      READ(1,*)H2
      DO 902 I=1,NO
      READ(1,*) O,DIST(I),O,O,VV(I),O
      DIST(I)=DIST(I)/10
902 CONTINUE
      FLAG=0
      GOTO 888
C READ(1,*) VAVG
C+++++ ALL DATA POINTS HAVE BEEN
READ

```

117

```

890      CONTINUE
      DO 901 I=1,MP1
      II=I-1
      J=1
      WRITE(*,999) II,B(I,J)
C ++++++ WRITES THE POLY COEFTS FROM
B
901      CONTINUE
      EPS=DIST(1)/41
C      WRITE(*,*) EPS,'STEP SIZE'
      VV2(1)=0.0
      DIST2(1)=0.0
C ++++++ USES EQNS TO GENERATE FIRST
40 PTS
      DO 917 I=2,41
      XX=DIST2(I-1)+EPS
C      WRITE(*,*) XX,'DIST2'
      C0=B(1,1)
      C1=B(2,1)
      C2=B(3,1)
      C3=B(4,1)
      C4=B(5,1)
      C5=B(6,1)
      C6=B(7,1)
      C7=B(8,1)

      YY=C0+C1*XX+C2*XX**2+C3*XX**3+C4*XX**4+C5*XX**5+C6*XX**6+C7*XX**7

      VV2(I)=YY
      DIST2(I)=XX
917      CONTINUE
      NTOTAL=41+NO
      , DO 918 I=42,NTOTAL
      VV2(I)=VV(I-41)
      DIST2(I)=DIST(I-41)
918      CONTINUE
C ++++++ NOW HAVE ARRAY WITH ALL EXPT PTS AND
INTERPOLATED
      NPTS=20
      M=7
      NSTART=1
C ++++++ REPEATS LEAST SQR FIT FOR ALL DATA
      IX=(INT(NTOTAL/15))
      DO 930 I2=1,IX
      NFIN=NSTART+NPTS-1
      DO 920 I=NSTART, NFIN
      II=I-NSTART+1
      X(II)=DIST2(I)
      Y(II,1)=VV2(I)
920      CONTINUE
      FLAG=0
      N=NPTS
      M=7
      CALL LSTSQR(X,Y,B,N,M,FLAG,MP1)

```



```

DO 921 I=NSTART,NFIN
    XX=DIST2(I)
    C0=B(1,1)
    C1=B(2,1)
    C2=B(3,1)
    C3=B(4,1)
    C4=B(5,1)
    C5=B(6,1)
    C6=B(7,1)
    C7=B(8,1)
C ++++++7TH ORDER POLYNOMIAL
C
    YY=C0+(C1*XX)+(C2*XX**2)+(C3*XX**3)+(C4*XX**4)+(C5*XX**5)+
    * (C6*XX**6) + (C7*XX**7)
    VV3(I)=YY
C    WRITE(*,*) DIST2(I),VV2(I),VV3(I),I,°    DIST, VV2,VV3°
921    CONTINUE
    NSTART=NFIN-4
930    CONTINUE
931    DO 922 I=1,NTOTAL
        DIST2(I)=DIST2(I)*10
922    CONTINUE
    DO 925 I=NFIN,NTOTAL
        VV3(I)=VV2(I)
925    CONTINUE
C ++++++ INTEGRATION
    THETA=0
    DELTAS=0
    DO 940 I=2,NTOTAL
        XX=DIST2(I)-DIST2(I-1)
        UUE=(VV3(I)+VV3(I-1))/2
        THETA=THETA+((UUE*(1-UUE))*XX)
        DELTAS=DELTAS+((1-UUE)*XX)
940    CONTINUE
    H=DELTAS/THETA
    NNUM=1
    WRITE(3,*) NNUM, ° STEP    DIST    DIST/THETA    VV2    VV3°
    WRITE(3,*) NTOTAL, °    NO PTS°
    WRITE(3,*) VVAVG, °    AVERAGE VEL m/s°
    WRITE(3,*) THETA, THETA2, °    THETA ,    THETA2°
    WRITE(3,*) DELTAS,DELTAS2, °    DELTAS,    DELTAS2°
    WRITE(3,*) H, H2, °    H,    H2°
    WRITE(*,*) THETA, DELTAS,H, °    THETA,    DELSTASTAR,    H °

    WRITE(*,*) THETA2,DELTAS2 ,H2, °THETA DELS H    old°
    DO 941 I=1,NTOTAL
        DST=DIST2(I)/THETA
        WRITE(3,*) I,DIST2(I),DST,VV2(I),VV3(I)
941    CONTINUE
999    FORMAT(I2,5X,E12.6)
998    STOP
    END
C
C

```

```

C      SUBROUTINE FOR LEAST SQUARES FIT
C
C      N=NUMBER OF DATA POINTS
C      M=DEGREE OF POLYNOMIAL TO BE FITTED
C      LL=THE NUMBER OF POLYNOMIALS TO BE FITTED
C      MM=AN INDEX TO READ DATA PTS FOR THE 1ST POLY BEING FITTED
AND STOP PRO
C      X(I) AND Y(I,J)  J=1          W(I)  WEIGHT OF THE  X,Y  CONSTANT
AT 1.0
C
      SUBROUTINE LSTSQR(X,Y,B,N,M,FLAG,MP1)
      INTEGER FLAG
      DIMENSION A(20,20),B(20,20),X(20),Y(20,1),W(20),C(20,20)
      DIMENSION IPVOT(20),INDEX(20,2),PIVOT(30)
      COMMON IPVOT,INDEX,PIVOT
      EQUIVALENCE (IROW,JROW),(ICOL,JCOL)
      J=1
      MM=0
      L=1
      LL=1
5      IF (MM.GE.LL) GO TO 1000
      IF (MM.NE.0) GOTO 25
15      CONTINUE
      DO 20 I=1,N
      W(I)=1.00
      DO 20 J=1,L
20      CONTINUE
C
C      FOLLOWING 11 STATEMENTS TO FORM THE COEFFICIENT MATRIX OF
THE
C      NORMAL EQUATIONS
C
25      DO 30 I=1,N
30      C(I,1)=1.0
      MP1=M+1
      DO 35 J=2,MP1
      DO 35 I=1,N
35      C(I,J)=C(I,J-1)*X(I)
      DO 40 I=1,MP1
      DO 40 J=1,MP1
      A(I,J)=0.0
      DO 40 K=1,N
40      A(I,J)=A(I,J)+C(K,I)*C(K,J)*W(K)
C
C      FOLLOWING 5 STATEMENTS TO FORM THE CONSTANT MATRIX OF THE
NORMAL EQNS
C
      DO 45 J=1,L
      DO 45 I=1,MP1
      B(I,J)=0.0
      DO 45 K=1,N
45      B(I,J)=B(I,J)+C(K,I)*Y(K,J)*W(K)
C
C      CALL SUBROUTINE TO SOLVE THE NORMAL EQUATIONS

```

```

C      CALL SOLVER (A,MP1,B,L,DET)
      DO 50 J=1,L
      DO 50 I=1,MP1
      II=I-1

C
50      CONTINUE
      MM=MM+1
      GOTO 5
      DO 999 I=1,20
          DO 998 J=1,20
              A(I,J)=0
              C(I,J)=0
998      CONTINUE
999      CONTINUE
1000     RETURN
      END

C
C
C
C      THIS SUBPROGRAM IS FOR MATRIX INVERSION AND SIMULT. LINEAR
EQNS
C
      SUBROUTINE SOLVER (A,N,B,M,DET)
      DIMENSION A(20,20),B(20,20),IPVOT(20),INDEX(20,2),PIVOT(20)

      COMMON IPVOT,INDEX,PIVOT
      EQUIVALENCE (IROW,JROW),(ICOL,JCOL)

C
C      FOLLOWING 3 STATEMENTS FOR INITIALIZATION
C
57      DET=1.0
      DO 17 J=1,N
17      IPVOT(J)=0
      DO 135 I=1,N

C
C      FOLLOWING 12 STATEMENTS FOR SEARCH FOR PIVOT ELEMENT
C
      T=0.0
      DO 9 J=1,N
          IF(IPVOT(J).EQ.1) GOTO 9
13      DO 23 K=1,N
          IF (IPVOT(K)-1) 43,23,81
43      IF (ABS(T).GE.ABS(A(J,K))) GO TO 23
83      IROW=J
          ICOL=K
          T=A(J,K)
23      CONTINUE
9      CONTINUE
      IPVOT(ICOL)=IPVOT(ICOL)+1

C
C      FOLLOWING 15 STATEMENTS TO PUT PIVOT ELEMENT ON DIAGONAL
C
      IF (IROW.EQ.ICOL) GOTO 109

```

```

73      DET=-DET
      DO 12 L=1,N
      T=A(IROW,L)
      A(IROW,L)=A(ICOL,L)
12      A(ICOL,L)=T
      IF (M.LE.0) GOTO 109
33      DO 2 L=1,M
      T=B(IROW,L)
      B(IROW,L)=B(ICOL,L)
      B(ICOL,L)=T
2      INDEX(I,1)=IROW
109     INDEX(I,2)=ICOL
      PIVOT(I)=A(ICOL,ICOL)
      DET=DET*PIVOT(I)
C
C      FOLLOWING 6 STATEMENTS TO DIVIDE PIVOT ROW BY PIVOT ELEMENT
C
      A(ICOL,ICOL)=1
      DO 205 L=1,N
205     A(ICOL,L)=A(ICOL,L)/PIVOT(I)
      IF (M.LE.0) GOTO 347
66      DO 52 L=1,M
52      B(ICOL,L)=B(ICOL,L)/PIVOT(I)
C
C      FOLLOWING 10 STATEMTNES TO REDUCE NON-PIVOT ROWS
C
347     DO 135 LI=1,N
      IF (LI.EQ.ICOL) GOTO 135
21      T=A(LI,ICOL)
      A(LI,ICOL)=0.0
      DO 89 L=1,N
89      A(LI,L)=A(LI,L)-A(ICOL,L)*T
      IF (M.LE.0) GOTO 135
18      DO 68 L=1,M
68      B(LI,L)=B(LI,L)-B(ICOL,L)*T
135     CONTINUE
C
C      FOLLOWING 11 STATEMENTS INTERCHANGE COLUMNS
C
222     DO 3 I=1,N
      L=N-L+1
      IF (INDEX(L,1).EQ.INDEX(L,2)) GOTO 3
19      JROW=INDEX(L,1)
      JCOL=INDEX(L,2)
      DO 549 K=1,N
      T=A(K,JROW)
      A(K,JROW)=A(K,JCOL)
      A(K,JCOL)=T
549     CONTINUE
3      CONTINUE
81      RETURN
      END

```

ROUGH WALL BOUNDARY LAYER PROGRAM

This program calculates the developement of two-dimensional turbulent boundary layers over rough surfaces in pressure gradients. It uses the method of Dvorak(1969).

Input variables:

RHT: the non-dimensional roughness height, K/C
 RDEN or LAMBDA: a roughness density parameter equal to surface area divided by frontal area of roughness, as discussed by Simpson (1973).
 REYNO: the Reynolds number $U_{ref} * C / \nu$, where C is a reference height, and ν is the viscosity
 THETA: the momentum thickness, normalized by C
 X: the streamwise position, normalized by C
 DELTA: the boundary layer thickness, normalized by C
 CFO: an initial guess of the skin-friction coefficient
 U: the non-dimensional velocity at the outer edge of the boundary layer, normalized by U_{REF} .

The calculations and output can be done in dimensioned form simply by choosing C =unit length, and U_{REF} =unit velocity.

```

PROGRAM MAIN
  DIMENSION THETA(50),U(50),X(50),DELS(50),HDELS(50),DU(50
1),DX(50),HCONV(50),CFI(50),UKONU(50)
  COMMON XX(4)
  OPEN(UNIT=1,FILE='',STATUS='OLD')
  OPEN(UNIT=3,FILE='',STATUS='NEW')
  READ(1,*) N
  DO 99 I=1,N
    READ(1,*) X(I),U(I)
99  CONTINUE
  READ(1,*) C,Uref,HCONV(1),THETA(1),RDEN,RHT
101 CONTINUE
  CFO=0.002
  REYNO=Uref*C/0.000016
  REYNOL=REYNO
  VIS=1.0/REYNO

  WRITE(3,22)

```

```

22      FORMAT('    ROUGH WALL BOUNDARY LAYER CALCULATION') 123
      WRITE(3,33) RDEN,RHT,REYNOL,C,UREF
33      FORMAT('LAMBDA=°,G10.3,° K/C=°,G10.3,° REYNO=°,G10.3,° °,
1      °C =°,G10.3,° UREF =°,G8.2)
      IF(RDEN.LT.2.0.OR.RDEN.GT.100) WRITE(3,100)
100     FORMAT('WARNING: LAMBDA VALUE IS BEYOND VALID
1      RANGE FOR THE CORRELATION °)
      NM1=N-1

C
C      to calculate the values of DU and DX
C
      DO 60 I=1,NM1
      DU(I)=(U(I+1)-U(I))/(X(I+1)-X(I))
60     DX(I)=X(I+1)-X(I)
C
C      To calculate the initial value of H delta-deltastar, equal to
C      G[Hconv]
C
      IF (HCONV(1).GT.1.6) GO TO 61
      HDELS(1)=3.3+EXP(0.4667-2.722*LOG(HCONV(1)-0.6798))
      GO TO 62
61     HDELS(1)=3.3+EXP(.4383-3.064*LOG(HCONV(1)-0.6798))
62     CONTINUE
      DELS(1)=HDELS(1)*THETA(1)
      JJJ=0

C
C      to find Cf (skin friction coefficient) for the first data point
C
      CFI(1)=CFOO(CFO,HCONV(1),THETA(1),VIS,U(1),RHT,RDEN,JJJ)
      UKONU(1)=SQRT(CFI(1)/2.0)*RHT*U(1)*REYNO

      DO 200 I=1,N
      ,
      IF(I.EQ.N) GO TO 200

C
C      The °old° or initial values to be used to find the values
C      at the next station are taken as the values at the present
C      station
C
      CFO=CFI(I)
      HCONVO=HCONV(I)
      THETAO=THETA(I)
      U1=U(I)
      U2=U(I+1)
      HDELISO=HDELS(I)
      DELSO=DELS(I)
      DUP=DU(I)
      DXP=DX(I)

C
C      The subroutine RUNGEK is called to integrate the differential
C      equations to find values for Hconv, theta, delta-deltastar,
C      H delta-delatstar, and Cf, at the next staion.
C
      IF (HCONVO.GT.3.0) GO TO 736

```

```

      CALL RUNGEK(CFO,HCONVO,THETAO,VIS,U1,U2,RHT,RDEN,JJJ,HDELISO,
1  DELSO,DUP,HCONVN,THETAN,DELSN,HDELSN,CFN,DXP)
C
C      updating of initial values
C
736      HCONVO=HCONVN
      THETAO=THETAN
      HDELISO=HDELSN
      DELSO=DELSN
      HCONV(I+1)=HCONVN
      THETA(I+1)=THETAN
      DELS(I+1)=DELSN
      HDELS(I+1)=HDELSN
      CFI(I+1)=CFN
      UKONU(I+1)=SQRT(CFI(I+1)/2.0)*RHT*REYNO*U(I+1)
200  CONTINUE
C
C      The subroutine OUTPUT is called to print the calculated values
C
      CALL OUTPUT (N,X,U,HCONV,THETA,UKONU,DELS,CFI,HDELS)
      CONTINUE
      WRITE(*,*) 'OLD LAMDA VALUE WAS ',RDEN
      WRITE(*,*) 'ENTER NEW LAMDA VALUE'
      READ(*,*) RDEN
      IF (RDEN.EQ.0) GOTC 102
      GOTO 101
102  CONTINUE
      STOP
      END
C*****
C
C      FUNCTION SUBROUTINE CFOO
C
C      This function returns the value of Cf, which is obtained
C      through a Neuton-Raphson iteration
C*****
      FUNCTION CFOO(CFI,HCONVP,THETAP,VIS,UP,RHT,RDEN,JJJ)
      CFO=CFI
C      IF (CFO.LT.0.00000) CFO=0.0          MOD ON 14 JAN 87
      IF (CFO.LT.0.0001) CFO=0.0001
10  CF11=CFO-(CFO-FNOO(CFO,HCONVP,THETAP,VIS,UP,RHT,RDEN,JJJ))/FNO(
1CFO,HCONVP,THETAP,VIS,UP,RHT,RDEN,JJJ)
C      CF222=CF11
C      IF (CF222.LT.0.0) CF222=0.0
C      WRITE(3,30), SQRT(CF222/2.0)*RHT*UP/VIS
C 30  FORMAT(' Utah*k/NU =',F15.9)
      IF(ABS((CFO-CF11)/CFO).LE.0.001) GO TO 20
      CFO=CF11
      GO TO 10
20  CFOO=CF11
C      IF (CFOO.LT.0.0) CFOO=0.0
      IF (CFOO.LT.0.0001) CFOO=0.0001
      RETURN

```

```

C*****
C
C      FUNCTION SUBROUTINE FNOO
C
C      This function returns the value of Cf for the input values
C      of the Cf guess,Hconv,theta,roughness height, and lambda.
C*****
C      FUNCTION FNOO(CFO,HCONV,THETA,VIS,U,RHT,RDEN,JJJ)
C      RETAHU=FN1(RDEN)
C
C      UTAH is the shear velocity
C
C      UTAHU=(RETAHU*VIS)/RHT
C      UTAH1=(5.0*VIS)/RHT
C      IF (CFO.LT.0.0) CFO=0.0
10    UTAHO=SQRT(0.5*U*U*CFO)
C      RETAH=(UTAHO*RHT)/VIS
C
C      the DELU are the shifts in the law of the wall intercepts in
C      equation 6 of Dvorak's paper
C
C      DELU1=FN2(RETAH,RETAHU,UTAHO,RDEN,UTAHU,JJJ,UTAH1)
C      DELU2=FN3(HCONV,CFO)
C      FNOO=2.0/((5.6*0.434294*LOG((U*HCONV*THETA)/VIS)+4.8-DELU1+DELU2)
1**2)
C      RETURN
C      END
C*****
C
C      FUNCTION SUBROUTINE FNO
C
C      This function returns the value of the derivative of the
C      function FNOO to be used in the Neuton-Raphson iteration
C      toward Cf.
C*****
C      FUNCTION FNO(CFO,HCONV,THETA,VIS,U,RHT,RDEN,JJJ)
C      EPS=0.1E-05
C      CFT1=CFO+EPS
C      CFT2=CFO-EPS
C      FNO=((CFT1-FNOO(CFT1,HCONV,THETA,VIS,U,RHT,RDEN,JJJ))-(CFT2-
1FNOO(CFT2,HCONV,THETA,VIS,U,RHT,RDEN,JJJ)))/(2.0*EPS)
C      RETURN
C      END
C*****
C
C      FUNCTION SUBROUTINE FN1
C
C      This function returns RETAH, the value of UTAH*k/NU at the upper
C      limit of the transitionally rough range; it represents fig.3
C      of Dvorak's paper.
C

```



```

C*****
      FUNCTION FN1(RDEN)
      IF (RDEN.LT.3.25) GO TO 10
      IF (RDEN.LT.3.75) GO TO 20
      IF (RDEN.LT.9.40) GO TO 30
      IF (RDEN.LT.25.0) GO TO 40
      IF (RDEN.GT.25.0) GO TO 50
      FN1=0.0
      RETURN
10    FN1=70.0
      RETURN
20    FN1=70.0-80.0*(RDEN-3.25)
      RETURN
30    FN1=30.0
      RETURN
40    FN1=30.0+2.564*(RDEN-9.4)
      RETURN
50    FN1=70.0
      RETURN
      END
C*****
C
C      FUNCTION SUBROUTINE FN2
C
C      This function returns the value of the law of wall shift
C      (delta U1)/UTAH; it represents fig.1 of Dvorak's paper.
C
C      RETAH is the input value of (U lambda)*k/v
C
C*****
      FUNCTION FN2(RETAH,RETAHU,UTAH,RDEN,UTAHU,JJJ,UTAH1)
      REAL KK,KKU,K1,KU1,KO
      DIMENSION C(4,9)
      COMMON XX(4)
C
C      If UTAH*k/NU  $\leq$  5.0 then flow is aerodynamically smooth, and
C      FN2=0
C
C      IF(RETAH.LE.5.0) GO TO 10
C
C      RETAHU is the upper limit of UTAH*k/NU for transitionally rough
C      surfaces. If our value of UTAH*k/NU is larger than this then
C      there is no need to fit the large polynomial necessary for the
C      transitionally rough regime.
C
C      IF(RETAH.LT.RETAHU) GO TO 30
C
C      for the fully rough case, calculate (delta U1)/UTAH for lambda
C      greater then or less than 5, according to fig.2 of Dvorak's paper
C
C      IF(RDEN.LE.5.0) GO TO 20
      FN2=5.6*0.434294*LOG(RETAH)-5.95*(1.103*0.434294*LOG(RDEN)-1.0)
      RETURN
10    FN2=0.0

```

```

20      RETURN
      FN2=5.6*0.434294*LOG(RETAK)+17.35*(1.625*0.434294*LOG(RDEN)-1.0)
      RETURN
C
C      Check to see if the transition region has been calculated before
C
30      IF(JJJ.GT.0) GO TO 65
C
C      Calculate the transition region by fitting a polynomial between
C      the smooth and fully rough regions
C
      KK=LOG(5.0)
      KCU=LOG(RETAKU)
      K1=1.0/UTAK1
      KU1=1.0/UTAKU
      C(1,1)=1.0
      C(1,2)=KK
      C(1,3)=KK**2
      C(1,4)=KK**3
      C(1,5)=0.0
      C(2,1)=0.0
      C(2,2)=K1
      C(2,3)=2.0*K1*KK
      C(2,4)=3.0*K1*KK**2
      C(2,5)=0.0
      C(3,1)=0.0
      C(3,2)=KU1
      C(3,3)=2.0*KU1*KCU
      C(3,4)=3.0*KU1*KCU**2
      C(3,5)=FN4(RETAKU,RDEN)
      C(4,1)=1.0
      C(4,2)=KCU
      C(4,3)=KCU**2
      C(4,4)=KCU**3
      C(4,5)=FN5(RETAKU,RDEN)
C      WRITE(3,39)
C 39      FORMAT(10X,' THE COEFFICIENT MATRIX')
C      DO 40 I=1,4
C 40      WRITE (3,41),(C(I,J),J=1,5)
C 41      FORMAT(10X,5F12.6)
      EPS=0.00001
      N=4
      CALL GJORD(C,N,EPS)
      JJJ=JJJ+1
65      KO=LOG(RETAK)
      FN2=XX(1)+XX(2)*KO+XX(3)*KO**2+XX(4)*KO**3
C      WRITE (3,70) ,(XX(I),I=1,4)
C 70      FORMAT(2X,'X(1)=',F12.6,' X(2)=',F12.6,' X(3)=',F12.6,
C      1      ' X(4)=',F12.6)
C      WRITE (3,80), FN2
C 80      FORMAT(10X,'FN2=',F12.6)
      RETURN
      END

```

C*****

```

C
C      FUNCTION SUBROUTINE FN3
C
C      This function returns the value of  $(\Delta U_2)/(\Delta U_1)$ 
C
C*****
C      FUNCTION FN3(H,CF)
C      MOD ON 14 JAN 87
C      IF(CF.LE.0) GOTO 11
C      G=SQRT(2.0/CF)*((H-1.0)/H)
C      IF(G.LT.6.7) GO TO 10
C      FN3=1.253*(G-6.7)
C      RETURN
10     FN3=0.404*(G-6.7)
C      RETURN
11     G=6.8
C      FN3=1.253*(G-6.7)
C      RETURN
C      END
C*****
C
C      FUNCTION SUBROUTINE FN4
C
C      This function returns the value of the derivative of
C       $(\Delta U_1)/(U \lambda)$  at the upper limit of the transitionally
C      rough region.
C
C*****
C      FUNCTION FN4(RETahu,RDEN)
C      EPS=0.01
C      RET1=RETahu+EPS
C      RET2=RETahu-EPS
C      FN4=(FN5(RET1,RDEN)-FN5(RET2,RDEN))/(2.0*EPS)
C      RETURN
C      END
C*****
C
C      FUNCTION SUBROUTINE FN5
C
C      This function returns the value of  $(\Delta U_1)/(\Delta U_2)$  at
C      the upper limit of the transitionally rough region, for FN2
C
C*****
C      FUNCTION FN5(RETahu,RDEN)
C      IF (RDEN.LE.5.0) GO TO 20
C      FN5=5.6*0.434294*LOG(RETahu)-5.95*(1.103*0.434294*LOG(RDEN)-1.0)
C      RETURN
20     FN5=5.6*0.434294*LOG(RETahu)+17.35*(1.625*0.434294*LOG(RDEN)-1.0)
C      RETURN
C      END
C*****
C
C      FUNCTION SUBROUTINE FN6
C

```

```

C      This funtion returns the value of F(H delta-deltastar), equation *
C      A1 of Dvorak's paper. *
C * * * * *
C      FUNCTION FN6(HDELS)
C      FN6=EXP(-3.512-0.617*LOG(HDELS-3.0))
C      RETURN
C      END
C * * * * *
C
C      FUNTION SUBROUTINE FN7
C
C      This function returns the value of Hconv, given the input
C      value of H delta-deltastar, based on equations A2 and A3 of
C      Dvorak's paper.
C * * * * *
C      FUNCTION FN7(HDELS)
C      IF (HDELS.LE.3.305) HDELS=3.305
C      IF(HDELS.GT.5.30) GO TO 10
C      FN7=0.6798+EXP((0.4383-LOG(HDELS-3.3))/3.064)
C      RETURN
10    FN7=0.6798+EXP((0.4667-LOG(HDELS-3.3))/2.722)
C      RETURN
C      END
C * * * * *
C
C      SUBROUTINE GJORD
C
C      This subroutine finds the coefficients for the log polynomial
C      in the transitionally rough range, using a Gauss-Jordan
C      elimination.
C * * * * *
C      SUBROUTINE GJORD(A,N,EPS)
C      DIMENSION A(4,9)
C      COMMON XX(4)
C      DO 2 J=6,9
C      DO 2 I=1,4
C      IF((J-5).EQ.1) GO TO 3
C      A(I,J)=0.0
C      GO TO 2
3    A(I,J)=1.0
2    CONTINUE
C      DO 112 I=1,4
C 112 PRINT 113,(A(I,J),J=1,9)
C 113   FORMAT(10X,9F12.6)
C      M=N+1
C      NPLUSM=N+M
C      DETER=1.0
C      DO 9 K=1,N
C      DETER=DETER*A(K,K)
C      IF (ABS(A(K,K)).GT.EPS) GO TO 5
C      WRITE(*,*) ' ° PIVOT TOO SMALL °

```

```

      RETURN
5     KP1=K+1
      DO 6 J=KP1,NPLUSM
6     A(K,J)=A(K,J)/A(K,K)
      A(K,K)=1.0
      DO 9 I=1,N
      IF(I.EQ.K) GO TO 9
      IF(A(I,K).EQ.0.0) GO TO 9
      DO 8 J=KP1,NPLUSM
8     A(I,J)=A(I,J)-A(I,K)*A(K,J)
      A(I,K)=0.0
9     CONTINUE
      DO 10 I=1,N
10    XX(I)=A(I,5)
      DO 102 I=1,4
C 102 PRINT 103, (A(I,J),J=1,9)
C 103     FORMAT(10X,9F12.6)
      RETURN
      END

```

```

C*****
C
C           SUBROUTINE RUNGEK
C
C           This subroutine contains the Runge-Kutta integration of the
C           momentum integral equation and Head's entrainment equation
C           to get the values of Hconv,theta,delta-deltastar,Hdelta-
C           deltastar, and Cf at the next station.
C*****
C           SUBROUTINE RUNGEK(CFO,HCONVO,THETAO,VIS,U1,U2,RHT,RDEN,JJJ,HDEL SO,
1DEL SO,DU,HCONVN,THETAN,DELSN,HDELSN,CFN,DX)
      UI=(U1+U2)/2.0
      DTHETO=(CFO/2.0-(HCONVO+2.0)*(THETAO/UI)*DU)*DX
      DDEL SO=(FN6(HDEL SO)-(DEL SO*DU/UI))*DX

      THETA1=THETAO+0.50*DTHETO
      DELS1=DEL SO+0.50*DDEL SO
      HDELS1=DELS1/THETA1
      HCONV1=FN7(HDELS1)
      IF (HCONV1.GT.3.0) GO TO 10
      CF1=CFO(CFO,HCONV1,THETA1,VIS,U1,RHT,RDEN,JJJ)
      DTHET1=(CF1/2.0-(HCONV1+2.0)*(THETA1/UI)*DU)*DX
      DDELS1=(FN6(HDELS1)-(DELS1*DU/UI))*DX
      THETA2=THETAO+0.5*DTHET1
      DELS2=DEL SO+0.5*DDELS1
      HDELS2=DELS2/THETA2
      HCONV2=FN7(HDELS2)
      IF (HCONV2.GT.3.0) GOTO 10
      CF2=CFO(CF1,HCONV2,THETA2,VIS,UI,RHT,RDEN,JJJ)
      DTHET2=(CF2/2.0-(HCONV2+2.0)*(THETA2/UI)*DU)*DX
      DDELS2=(FN6(HDELS2)-(DELS2*DU/UI))*DX
C
      THETA3=THETAO+DTHET2
      DELS3=DEL SO+DDELS2

```

```

HDELS3=DELS3/THETA3
HCONV3=FN7(HDELS3)
IF (HCONV3.GT.3.0) GOTO 10
CF3=CFOO(CF2,HCONV3,THETA3,VIS,U2,RHT,RDEN,JJJ)
DTHET3=(CF3/2.0-(HCONV3+2.0)*(THETA3/U2)*DU)*DX
DDELS3=(FN6(HDELS3)-(DELS3*DU/U2))*DX
C
THETAN=THETA0+(DTHETO+2.0*DTHET1+2.0*DTHET2+DTHET3)/6.0
DELSN=DELS0+(DDELS0+2.0*DDELS1+2.0*DDELS2+DDELS3)/6.0
HDELSN=DELSN/THETAN
HCONVN=FN7(HDELSN)
CFN=CFOO(CF3,HCONVN,THETAN,VIS,U2,RHT,RDEN,JJJ)
C
RETURN
C
10 HCONVN=6.0
RETURN
C
END
C
C
C*****
C 10 HCONVN=6.0
C RETURN
C
C END
C
C*****
C
C SUBROUTINE OUTPUT
C
C This subroutine controls the output of the calculated values
C
C*****
C
C SUBROUTINE OUTPUT (N,X,U,HCONV,THETA,UKONU,DELS,CFI,HDELS)
C
C DIMENSION X(50),U(50),HCONV(50),THETA(50),UKONU(50),DELS(50),
1 CFI(50),DELTASTAR(50),DELTA(50),HDELS(50)
C
C WRITE (*,*) °X/C U/UE H THETA/C DELS/C
1 CF/2°
C WRITE(3,*) ° X/C U/Ue H THETA/C DELS/C DELTA/C
1 CF/2°
C
C J=0
DO 10 I=1,N
IF(HCONV(I).GT.3.0.AND.J.EQ.0) THEN
WRITE (*,3)
WRITE (3,3)
J=1
END IF

```

3

FORMAT('FLOW HAS SEPARATED ')

132

CFI(I)=CFI(I)/2

DELTA(I)=THETA(I)*(HCONV(I)+HDELS(I))

DELTASTAR(I)=DELTA(I)-DELS(I)

WRITE(*,2) X(I),HCONV(I),THETA(I),DELTASTAR(I),

1 CFI(I)

WRITE(3,44) X(I),U(I), HCONV(I),THETA(I),DELTASTAR(I),DELTA(I),

1 CFI(I)

10

CONTINUE

WRITE(3,4)

C

4

FORMAT(////)

2

FORMAT(/,E10.4,E10.4,E10.4,E10.4,E10.4)

44

FORMAT(/,G10.4,G10.4 ,G10.4 ,E10.4 ,E10.4 ,E10.4,E10.4)

C

RETURN

END

APPENDIX D**TRAVERSING GEAR DESIGN
AND DATA ACQUISITION SYSTEM**

D.2

WIRING DIAGRAM FOR CONTROLLER

BLACK BOX

MOTOR Superior M061-FD02 Stepping Motor
 5 Volts DC 1.0 Amps per winding
 5.0 Ohms per winding 10.4 mH per phase
 35 oz-in running torque

POWER SUPPLY Acme Electric PS 59134 Modular
 Input 105-125 V 60 Hz
 Output 24 V DC 0.5 to 6 Amp
 Ripple Voltage less than 1 mV

MOTOR DRIVER DMA-64 Step Motor Driver
 Input TTL compatible Logic '0' 0-.8Vdc
 Logic '1' 3.5 - 5.0 Vdc
 Power requirement 15 to 38 Vdc
 0 to 77 mA
 Output current rating 6.5 Amps per phase max.

	EXCITATION											
	SINGLE				DUAL				HALF-STEP			
	$\phi 1$	$\phi 2$	$\phi 3$	$\phi 4$	$\phi 1$	$\phi 2$	$\phi 3$	$\phi 4$	$\phi 1$	$\phi 2$	$\phi 3$	$\phi 4$
CW	ON				ON	ON			ON	ON		
		ON				ON	ON		ON		ON	
			ON				ON	ON		ON		ON
				ON	ON			ON	ON			ON
	ON				ON	ON				ON	ON	
		ON				ON	ON				ON	ON
			ON				ON	ON				ON
CCW				ON	ON			ON	ON			ON
	ON				ON	ON			ON	ON		

TRUTH TABLE 4 PHASE MOTOR

CLOCK LINE INPUTS

SWITCHING SEQUENCE*		
STEP	SWITCH #1	SWITCH #2
1	1	5
2	1	4
3	3	4
4	3	5
1	1	5

* To reverse direction read chart up from bottom

SWITCHING SEQUENCE

8 STEP INPUT SEQUENCE

D.4 Overall Equipment Test Set-Up

END

1 3|0 9|9 0

FIN