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An Investigation of the Effects of Battle-Damage Repair Patches on the Aerodynamic Performance of an Airfoil

by

Kevin J. Black, B.Eng.

Thesis

Presented to the Faculty of Graduate Studies and Research of

Carleton University

in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF ENGINEERING

Department of Mechanical and Aerospace Engineering

Ottawa-Carleton Institute for Mechanical and Aerospace Engineering

Carleton University

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The undersigned hereby recommend to
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**An Investigation of the Effects of Battle-Damage
Repair Patches on the Aerodynamic Performance of
an Airfoil**

submitted by

Kevin J. Black, B.Eng.

in partial fulfillment of the requirements
for the degree of Master of Engineering

Chair, Department of Mechanical and Aerospace Engineering

Thesis Supervisor

Carleton University

August 1995

Abstract

An experimental investigation of the aerodynamic characteristics of a C/F-18 wing section with simulated Aircraft Battle-Damage Repair (ABDR) patches is reported. The tests were performed in a low speed wind tunnel with a passive low-correction test section. Lift coefficients for the airfoil were obtained from the pressure distribution and drag coefficients were determined using the wake traverse technique. Lift and drag coefficients for two-dimensional, square, and round patches of three different thicknesses were obtained with patches located at three different chordwise positions. Coefficients of drag per unit span were determined for the patch-centreline plane of all patches and in several off-centreline planes for two patches.

As expected, thicker patches lead to increased drag. Patches near the leading edge increased drag more than patches at other chordwise positions. Round patches have a larger incremental effect on drag than square patches. Surprisingly, at relatively high angles of attack, a few patch configurations resulted in lower drag than for the clean airfoil; this is ascribed to low-Reynolds-number effects and is unlikely to occur at full-scale conditions. Results of the investigation were compared to a previous computational study. In broad general terms, the measured and computed effects of patches were of comparable magnitude but the results did not compare well in detail at angles of attack above 3° .

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KEVIN J. BLACK

Carleton University

August 1995

*This is dedicated to my
wonderful, loving, supportive, and encouraging parents.*

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List of Symbols and Abbreviations

c, c_s	chord length of airfoil; chord length of slat
C_d, C_{dp}, C_{dc}	drag coefficient per unit span; with patch; clean airfoil
ΔC_d	incremental drag coefficient per unit span at a probe position
ΔC_D	drag increment due to a patch
C_l, C_{lp}, C_{lc}	lift coefficient per unit span; with patch; clean airfoil
C_n	normal force coefficient per unit span
C_x	axial-force coefficient per unit span
g	gap between slats at tunnel wall
h	step height
H	height of test section
K	calibration constant of test section $[(P_{c1} - P_{c2})/(1/2\rho V^2)]$
P_{c1}, P_{c2}	reference pressures on tunnel contraction section
P_o, P_{of}, P_{ow}	total pressure: generic; free stream; in the wake
P_s, P_{sf}, P_{sw}	static pressure: generic; free stream; in the wake
Re	Reynolds number based on airfoil chord
Re_h	Reynolds number based on patch thickness and friction velocity
V	freestream velocity
w_{eff}	effective patch width
x	airfoil coordinate in chordwise direction
y	airfoil coordinate; distance across the wake
α	angle of attack in degrees
ρ	density of air
AOA	angle of attack
OAR	open area ratio $[g/(c_s + g)]$

1. Introduction

Combat aircraft may suffer battle damage. The damage can be diagnosed and treated with the Canadian Armed Forces system of Aircraft Battle-Damage Repair (ABDR). Due to the quick response required during combat conditions, some of the repairs may simply be patches installed over the damaged area. If these protruding patches are present on lifting surfaces, the patch's effect on the aerodynamics of the aircraft could be substantial.

Carnegie (1992) carried out a preliminary investigation of the effects of ABDR patches on CF-18 airfoils. Carnegie experimentally investigated the boundary layer growth produced by forward- and backward-facing steps. Since the chordwise patch length is much greater than the patch thickness, ABDR patches can be thought of as independent forward- and backward-facing steps. Carnegie's experimental investigation provided step-flow correlations that were implemented into a computer model that predicted the lift and drag on the CF-18 airfoil. From his investigations, it was determined that if the patches were not very close to the leading edge, they could be as thick as 0.5" (1.27 cm) full-scale and not have serious effects on CF-18 wing lift at attack angles below stall. It was also determined that drag increases were approximately proportional to increases in patch thickness and drag increases were substantial for all angles of attack and patch positions. However, Carnegie's conclusions were based primarily on computations and need to be verified by experimental results.

The purpose of this thesis is to determine experimentally the effects of ABDR patches on aerodynamic performance of the CF-18 airfoil. The results of the experimentation are compared to Carnegie's conclusions.

The experiments involved two-dimensional tests on a model of a CF-18 airfoil

Figure 1.1: Computed 3-D pressure distribution on a F-18 wing, $C_L \approx 0.3$ (courtesy of Analytical Methods Inc.)

section in one of Carleton University's low-speed wind tunnels. The two-dimensionality of the tests is not a serious limitation on the usefulness of the results. As seen in Figure 1.1, flow over most of the CF-18 wingspan is two-dimensional at low angles of attack. Conversely, flow will be highly three-dimensional at high angles of attack, but the flow will also be separated and only slightly affected by ABDR patches.

The flow in the experiments was incompressible; therefore, the results are only valid for sub-critical Mach numbers, that is, when there are no shock waves in the flow field. However, the results are still useful for many flight conditions, including the critical take-off and landing regimes.

The experiments investigated three patch thicknesses, with patches located at 6%, 25% and 50% chord. Patch plan shapes were two-dimensional, i.e., strips, round

and square. The effects of changing the airfoil angle of attack and Reynolds number were also investigated.

Chapter 2 of this thesis reviews the literature of related research. Chapter 3 outlines the equipment design and configuration and describes the procedures involved in the calibration, testing and data analysis. Chapter 4 examines and discusses the experimental results, and comparisons to Carnegie's work are made. Finally, conclusions and recommendations are recorded in Chapter 5.

2. Literature Review

Since the length of a ABDR patch would normally be much greater than its thickness, aerodynamic effects of a two-dimensional patch can be considered to be caused by independent forward- and backward-facing steps. An extensive literature review of forward- and backward-facing steps was carried out by Carnegie (1992) and will not be reproduced here.

Any recent research, or papers not covered by Carnegie on forward/backward-facing steps or airfoil patches will be discussed here, although no research of which the author is aware has focused on the change in aerodynamic properties due to airfoil patches. Most research has focussed on modelling the drag effects of excrescences that are permanent fixtures on an aircraft, such as wing joints, Pitot tubes, fairings and control gaps. A review of available literature revealed very little information on the loss of lift attributed to aircraft excrescences.

An extensive review and summary of available data on drag of aircraft excrescences has been carried out by Young and Paterson (1981). They also discuss boundary layer characteristics and distributed roughness in boundary layers. As Young and Paterson state, combinations of the following phenomena contribute to a drag increase on aircraft excrescences and roughness:

- Pressure forces on the excrescence itself;
- Changes in local surface shear forces forward and aft of the excrescence;
- The added disturbance could potentially induce separation;
- The excrescence could affect the downstream boundary layer.

All of the above factors will be affected by the pressure gradient across the excrescence. Young and Paterson include a short section on the effect of excrescences on C_{Lmax} of airfoils with most of the studies covered examining roughness such as hoar frost. Their summary shows that a wing with flap extended has the greatest sensitivity with respect to C_{Lmax} , while a leading edge slat reduces the sensitivity to roughness. The flap movement increases suction at the leading edge and magnifies the roughness effect on C_{Lmax} . A leading edge slat tends to reduce the suction peak on the wing, thus reducing sensitivity to roughness or excrescences.

A great deal of the data in the review of Young and Paterson was obtained from an extensive drag study of aircraft excrescences performed by Gaudet and Winter (1973). Two-dimensional steps and ridges, circular cylinders and wings mounted normal to the surface, holes and fairings were tested over a Mach number range of 0.2 to 2.8 and a range of Reynolds numbers. Gaudet and Winter determined that chamfering or rounding the upper corners of two-dimensional ridges was beneficial at subsonic speeds, but far less beneficial at supersonic speeds. The steps, ridges and grooves tested were small compared with the boundary layer thickness, the top of the steps being within the logarithmic region of the undisturbed turbulent boundary layer. Gaudet and Winter tested cylindrical excrescences mounted normal to the surface, but none of the cylinders tested had a height-to-diameter ratio less than one, so their data cannot be applied to circular ABDR patches.

An experimental and computational study on "Small Two-Dimensional Surface Excrescences on Aircraft Wings Approaching Separation" was performed by Alhusein and Cockrell (1992). Alhusein and Cockrell investigated the effects of square cross-section ridges in promoting premature flow separation on aircraft wings at high-lift configurations. A strongly adverse pressure gradient was established on a wind tunnel floor in order to induce flow separation. Two-dimensional surface excrescences were

placed well upstream of the separation region. The excrescences were representative of ice accumulation or manufactured discontinuities such as a plate joint. If the discontinuities lay within the law of the wall of the boundary layer and were located upstream by at least 14 excrescence heights, the excrescences had a negligible effect on inducing flow separation downstream. Computational studies were performed with an integral lag-entrainment boundary-layer prediction technique originally developed by Green, Weeks, and Brooman (1973). Good agreement was found between the experimental and computational results.

Recent studies of flow over step faces have involved advanced instrumentation and measurement techniques such as the study of reattaching flow over a backward-facing step by Kasagi et al. (1993). Detailed turbulence measurements were made upstream and downstream of the step with a three-dimensional particle tracking velocimeter (3-D PTV) which measured all velocity components. The experimental results found the mean reattachment length to be $6.51h$ downstream of the step. The mean reattachment length was defined based on the location of the 50% forward flow point. Kasagi et al. determined that the maximum Reynolds normal and shear stresses were located in the separating free shear layer upstream of the reattachment. The authors also reported that near the reattachment point, the spanwise normal stress was the largest among the three normal Reynolds stresses. In the standard $k-\epsilon$ turbulence model, the ratio of Reynolds shear stress to turbulent kinetic energy is assumed to be 0.15. Kasagi et al. measured larger values than 0.15 just downstream of the separation and they suggested this was one reason why the reattachment length predicted by the $k-\epsilon$ model did not agree with experimental results.

Disagreement between $k-\epsilon$ models and experimental results are shown in studies such as Acharya et al. (1994) which compared experimental results and the standard $k-\epsilon$ model to a non-linear $k-\epsilon$ model. The non-linear model retained the tensorially

invariant eddy viscosity of the standard $k-\epsilon$ model and in order to account for the nonisotropic behaviour in the turbulent stresses, added the second-order derivatives of the streamwise and cross-stream velocities to the Boussinesq approximation. The non-linear model performed better at predicting production and dissipation of the turbulent kinetic energy near reattachment. Both $k-\epsilon$ models performed well close to the reattachment region and core flow regions while both models were inadequate in the separated and shear-layer regions close to the two-dimensional rib.

3. Apparatus and Experimental Procedures

3.1 Apparatus

The experiments involved the testing of a CF-18 airfoil model. An important requirement in aerodynamic testing is dynamic similarity; this requires, strictly speaking, maintaining the same Reynolds numbers for the model as for the full-scale object. Although full-scale Reynolds numbers could not be achieved, attempting to maintain Reynolds number as high as possible drove the design of the test section and model airfoil. The design and construction of the test section and model airfoil, as well as the remainder of the apparatus, will be discussed below.

3.1.1 Wind Tunnel and Test Section

The experimental testing was performed in a 0.51 m x 0.76 m (20" x 30") test section of a closed circuit wind tunnel at Carleton University. The wind tunnel fan is powered by a 44.76 kW induction motor and the fan's rotation speed is controlled by a magnetic clutch. The wind tunnel is capable of speeds up to about 75 m/s (170 mph) with the blockage-tolerant test section used in the investigation. A breather vent at the downstream end of the test section maintains atmospheric pressure in the tunnel test section.

If the model experiments are to be meaningful, the Reynolds number (Re_h) based on patch thickness and friction velocity must be greater than about 50 in order to ensure fully rough aerodynamic flow similar to the full-scale flow. As well, the airfoil patch must be correctly scaled relative to the airfoil model. The two requirements stated above limited the minimum size of the airfoil, while wind tunnel blockage

limited the maximum size of the model. A large wind tunnel was desirable for testing. The available tunnel would only accommodate a 10" (25.4 cm) chord airfoil without excessive blockage; however, up to a 24" (60.96 cm) chord airfoil would be allowable without significant blockage through the use of a blockage-tolerant test section. This blockage-tolerant test section design is based on work by Parkinson (1990) and is illustrated in Figure 3.1. A solid wall on the suction side of the airfoil is replaced by a series of uniformly spaced airfoil slats. The slats allow air to pass in and out of the test section and a plenum on the other side of the slats.

The wind tunnel has a maximum speed capability of about 240 ft/s (75 m/s) with the slotted sidewall of the blockage-tolerant test section. At 240 ft/s, a Re_h of 50 would correspond to a patch thickness of about 0.013" (0.33 mm) which corresponds to 0.0625" (1.59 mm) on a full-scale CF-18 wing just over 9' (2.74 m) chord (five times the model chord). The use of the blockage-tolerant test section enabled use of a suitable Re_h and allowed the experiments to cover a practical range of full-scale patch thicknesses (i.e., 1/16" (1.59 mm) and greater).

One parameter of this test section is the open area ratio (OAR), defined by $OAR = g/(c_s + g)$ where c_s is the slat chord and g is the gap between the slats (see Figure 3.1). The c_s and g values for this test section are 10.16 cm (4") and 27.464 cm (10.8125"), respectively, for an OAR value of 0.63. Parkinson's work has shown that an OAR in the 60-70% range provides a low-correction capability for the test section. If the chord-to-tunnel-height ratio is between 0-0.70, corrections to the order of less than 1% are required for airfoil pressure distributions and lift coefficients. See Figure 3.2 for an illustration of the effectiveness of a blockage-tolerant test section.

Another parameter is the chord-to-height ratio (c/H) (see Figure 3.1). The c/H ratio for the present model airfoil and test section is 0.733 which falls within the acceptable limits indicated by Parkinson's work (see Figure 3.2).

Figure 3.1: Test Section Schematic

Figure 3.2: Effect of Airfoil/Tunnel Size Ratio on Lift: a) Theory, b) Experiment. From Parkinson (1990) where $g/S = OAR$, $c/H =$ Chord to Tunnel Height Ratio, $C_{LT}/C_{LF} =$ Lift Coefficient in the Tunnel Normalized by Free-Air Lift Coefficient, and $m =$ Lift Curve Slope.

Figure 3.3: Cross Sectional View of the Slat Construction

As noted in Figure 3.1, the test section is of plywood construction with a plexiglass door for access to the section.

The airfoil slats are constructed in the following manner: 4" x 1/8" (10.16 cm x 0.32 cm) steel slats form the support core and two strips of contoured styrofoam are taped to each core to form a NACA0015 airfoil. See Figure 3.3 for a cross-sectional view of the slat construction. The NACA0015 airfoil was chosen for the slat profile since it was the airfoil used by Parkinson (1990).

3.1.2 Airfoil Design

The 2D model airfoil (22" (55.88 cm) chord) used in the experiment is a 1:5 scale model of a CF-18 airfoil. The airfoil is representative of a cross-sectional slice taken at the 64% (142.2" (3.61 m)) semi-span location on the CF-18 aircraft (Lambert 1994).

Thirty-one coordinate values were available to define the airfoil section shape, but the available coordinates did not provide sufficient detail for manufacturing purposes. For a more accurate profile, more coordinates were required near the leading edge of the airfoil. These coordinates were obtained using a CAD package and a FORTRAN program called INV AIRF: INV AIRF uses inviscid, incompressible, two-dimensional flow calculations to find the pressure distribution around specified airfoil sections. The CAD package was utilized to draw splines between the known coordinates. Thirteen interpolated points were chosen from the splines to supplement the 31 available coordinates. INV AIRF was then used to calculate pressure distributions at various angles of attack using the 31 available coordinates; these would act as reference pressure distributions when checking the validity of the interpolated points. Pressure distributions were then calculated with all 43 points. The interpolated points were slightly adjusted until smooth, continuous pressure distributions were produced by INV AIRF. Pressure distributions were calculated for 0° , 2° , 4° and 6° angles of attack. Smooth pressure distributions that were similar to the reference pressure distributions indicated that the interpolated points were located at points on a valid airfoil surface. If the interpolated points were not located on the true airfoil surface, the calculated pressure distributions would have spikes or dips in the distribution. The coordinates of the final airfoil profile are listed in Table 3.1.

The calculated pressure distributions were also employed to determine suitable chordwise positions for the static taps. Static taps were concentrated in areas of high pressure gradients (e.g., near the leading edge) and spaced less densely in areas of

Table 3.1: CF-18 Profile Coordinates

TOP SURFACE		BOTTOM SURFACE	
x/c	y/c	x/c	y/c
1.00000	0.009154	0.0000819	-0.0003002 *
0.83646	0.01562	0.0002185	-0.0005095 *
0.75469	0.01886	0.0009282	-0.0010644 *
0.686873	0.021543 *	0.00197	-0.00143
0.62136	0.02394	0.0037108	-0.0019052 *
0.52272	0.02595	0.0059272	-0.0024106
0.42409	0.02658	0.0095393	-0.0030096 *
0.32547	0.02594	0.01380	-0.00352
0.22685	0.02356	0.02960	-0.00473
0.12822	0.01839	0.04931	-0.00554
0.08877	0.01515	0.08877	-0.00626
0.04931	0.01097	0.12822	-0.00665
0.02960	0.00830	0.22685	-0.00778
0.01380	0.00552	0.32547	-0.00890
0.0087834	0.0043571 *	0.42409	-0.00909
0.00592	0.00354	0.52272	-0.00816
0.0035682	0.0026947 *	0.62136	-0.00624
0.00197	0.00200	0.689741	-0.0041653 *
0.0010367	0.00149 *	0.74950	-0.00194
0.0007581	0.00130 *	0.87475	0.00307
0.0002487	0.000816 *	1.00000	0.008056
0.0000486	0.0004612 *		
0.00000	0.00000		

* denotes interpolated points

low pressure gradients (e.g., towards the trailing edge). The static tap placement is illustrated in Figures 3.4 and 3.5.

The airfoil was machined from 2024 aluminum. This material was chosen for its good machining qualities and because it does not warp as much as other aluminum alloys. During the machining process, the airfoil was stress-relieved at 375 F (190 °C).

The entire airfoil was machined until it was 0.020" (0.508 mm) thicker than the required profile. At this point, channels for the static pressure tubes were machined into the airfoil's surface. Since the airfoil was very thin (less than 0.75" (1.91 cm)), the static tubing had to be embedded in the airfoil's surface. Brass tubing was used for the static tube material. After the tubes were tested for leaks, they were outfitted with brass termination plugs as illustrated in Figure 3.6. The unique tube termination configuration was employed near the leading edge of the airfoil where there was not enough space to use the standard termination configuration. The tubes were pressed into the machined channels and epoxied into place. Channel depth and width are illustrated in Figure 3.6. The channel paths are shown in Figures 3.4 and 3.5. The channels exit the side of the airfoil in the same area in order to facilitate connections through the exterior of the test section. After the epoxy cured, the airfoil was machined down to the required profile. During this process, a portion of the brass tube was milled away, so that the finished airfoil and tube surfaces were flush (see Figure 3.6). The final cut left 4" (10.16 cm) along each span-edge at the slightly larger profile as an acceptable means of trying to keep machining costs down.

After the finishing pass, the static tap holes (0.031" (0.79 mm) diameter) were drilled perpendicular to the airfoil surface. The final tap coordinates, shown in Table 3.2, were obtained from the milling machine readout.

Figure 3.4: Static Tap Positions – Bottom Surface (Viewed from the Top)

Figure 3.5: Static Tap Positions - Top Surface

Figure 3.6: Tube Construction and Placement. (Dimensions in Inches.)

Table 3.2: Static Tap Coordinates

TOP SURFACE			BOTTOM SURFACE		
#	x/c	y/c	#	x/c	y/c
1	0.94398	0.01136	19	0.00142	-0.00163
2	0.87926	0.01392	20	0.00284	-0.00204
3	0.79818	0.01750	21	0.00591	-0.00277
4	0.68651	0.02156	22	0.01382	-0.00389
5	0.57455	0.02546	23	0.02960	-0.00473
6	0.49409	0.02661	24	0.04931	-0.00554
7	0.39546	0.02686	25	0.08877	-0.00626
8	0.32515	0.02594	26	0.12821	-0.00665
9	0.22655	0.02355	27	0.22685	-0.00885
10	0.13816	0.01910	28	0.39648	-0.00915
11	0.08864	0.01550	29	0.51421	-0.00828
12	0.04909	0.01131	30	0.62136	-0.00624
13	0.02955	0.00865	31	0.75469	-0.00174
14	0.01382	0.00589	32	0.87475	0.00307
15	0.00591	0.00390	33	0.94398	0.00583
16	0.00284	0.00276			
17	0.00142	0.00208			
18	0.00000	0.00000			

Table 3.3: Matrix of Patch Sizes

NOMINAL SIZE	MODEL THICKNESS	FULL-SCALE THICKNESS
Thin	0.015" (0.38 mm)	0.075" (1.91 mm)
Medium	0.060" (1.52 mm)	0.300" (7.62 mm)
Thick	0.125" (3.18 mm)	0.625" (15.88 mm)

3.1.3 ABDR Patches

Three patch configurations were employed in the experimentation: 2D, square and round patches. The chordwise length of all the patches was 55.88 mm (2.2"), or 10% of the chord. It was felt that 10% of the chord would be the longest patch length used in an actual repair and this length would have the most impact on drag values. Patch thicknesses are shown in Table 3.3. These model patch thicknesses were chosen because: i) the actual patch thicknesses corresponded to the minimum, mid-range and maximum thickness of patch materials used on CF-18's; and ii) the model patch thicknesses corresponded to available standard thicknesses of aluminum sheet. The patch thicknesses will be referred to as Thin, Medium and Thick throughout this document.

0.031" (0.79 mm) diameter holes were drilled in the patches to line up with static tap holes that would have been covered by installed patches. If a drilled hole did not cover any static taps, the hole was filled with model filler in order to maintain a smooth surface.

A schematic of the patches is presented in Figure 3.7. The 2D, square and round patches all had square, 90° edges at the leading and trailing edges of the patch (i.e., no bevels).

During experimentation, the patches were installed with their upstream edges at each of the following chordwise positions on the suction surface: 0.0568c (hereafter referred to as 0.06c), 0.25c and 0.50c. The patches were held in position with double

Figure 3.7: Patch Dimensions.

Figure 3.8: Side View of Probe and Airfoil. (Dimensions in Inches.)

sided tape which was approximately 0.002" (0.051 mm) thick. Securing of the thick patches was augmented by a centimetre (0.4") strip of epoxy across the width of the patch since double-sided tape was not strong enough by itself. The installed patch positions are illustrated in Figure 3.8 with dashed lines. As seen in Figure 3.8, a patch at 0.06c has two taps that measure the static pressure of the flow over the patch. Another tap is situated close to the leading edge of the patch. When a patch is in the 0.25c or 0.50c positions, there is one tap to provide a measure of the static pressure on top of the patch. A patch in the 0.50c position also has a static tap close to the leading edge of the 2D and square patches, but the same tap is not quite as close to the leading edge of the circular patch.

3.1.4 Pitot and Static Probe and Traversing Gear

The profile drag of the airfoil was determined using the wake traverse method (see Section 3.2.3). Measurements from the wake traverse were collected by a Pitot and static probe unit that was horizontally moved by a stepper-motor driven traverse gear. The static probe was a modified Pitot-static probe. The Pitot hole diameter of the original Pitot-static probe was too large for the accurate spatial resolution required for the Pitot measurements during the wake traverse. Rather than machining a new Pitot-static probe, the Pitot hole on the original Pitot-static probe was filled and the static pressure capabilities of the probe were retained. Pitot pressure measurement was provided by mounting a 1/32" (0.79 mm) I.D. (0.042" (1.07 mm) O.D.) tube adjacent to the static probe (0.120" (3.05 mm) O.D.). The static and Pitot probes were separated by a distance of approximately 32 mm (1.25"), while the probe tips were located in the same vertical plane. The position of the probes relative to the airfoil is illustrated in Figures 3.8 and 3.9.

Binary signals from the printer port of a microcomputer were sent to an interpreter unit which commanded the stepper-motor which drove the traverse gear. The bi-directional motor turned a brass screw (20 threads/inch) which was threaded through a metal block to which the probe was secured. The guides supporting the block were long enough to allow a horizontal traverse of up to 180 mm (7.09"). As in Carnegie (1992), it was found that a positional accuracy of 0.1 mm (0.004") could be achieved over a traverse distance of 70 mm (2.76"). The traverse gear support was mounted so that the tip of the Pitot tube was 14.5 cm (5.7") downstream of the airfoil's trailing edge and the probe was approximately in line with the airfoil's centreline (see Figures 3.8 and 3.9).

Figure 3.9: Plan View of Probe and Airfoil. Dimensions in Inches.

3.1.5 Instrumentation Setup and Data Acquisition

A schematic of the instrumentation setup is shown in Figure 3.10. The Pitot and static tubes and static taps in the tunnel and on the airfoil provided pressure signals to the calibration manometers, transducers and manometer bank. The transducers were connected to the computer through Sciometrics Labmate Data Acquisition hardware. The computer communicated with the traversing gear stepper-motor through an interpreter unit. Each portion of the instrumentation system will be discussed below.

To automate the data acquisition, pressure transducers were utilized to measure the $(P_o - P_{c2})$, $(P_{c1} - P_{c2})$ and $(P_{c2} - P_s)$ pressure differences. $(P_{c1} - P_{c2})$ is a reference pressure difference measured between two static pressure taps located in the wall of the tunnel contraction upstream of the test section. One tap is at the inlet of the contraction (P_{c1}) and the other is near the outlet (P_{c2}) . $(P_{c1} - P_{c2})$ provides a measure

Figure 3.10: Schematic of Data Acquisition Apparatus

of freestream dynamic pressure in the test section. $(P_o - P_{c2})$ is the pressure difference measured between the total pressure (P_o) of the Pitot tube probe and P_{c2} . $(P_{c2} - P_s)$ is the pressure difference between the reference static pressure, P_{c2} , and the static pressure (P_s) sensed by the static probe.

Two Setra pressure transducers (model no. 239) with a range of ± 3450 Pascals (± 0.5 psid, ± 2.5 Volts) and a quoted hysteresis of $\pm 0.4\%$ full-scale were used to measure the $(P_o - P_{c2})$ and $(P_{c1} - P_{c2})$ pressure differences. An Omega pressure transducer (model no. PX170-DV) with a range of 0–3490 Pascals (0–14" H_2O , 0–35 mV) and a quoted hysteresis of 0.25% full-scale was used to measure the $(P_{c2} - P_s)$ pressure difference. As seen in Figure 3.10, vertical water-filled manometers were connected in parallel to the transducers to provide calibration. The calibration curves drifted only very slightly during the course of the experimentation (see Section 3.2.1).

A Sciometrics Labmate 7000 Data Acquisition system provided 12 bit A/D conversion of the pressure transducer outputs. The Labmate 7000 utilizes a 12 bit-

plus-sign, dual-slope, integrating A/D converter. The analog voltage is integrated over a period of time to determine the digital value. The A/D converter gives a digital answer between 0 and 4095 along with a sign bit and an over-range bit. The software will issue an over-range error if the over-range bit is on. Since it is a 12 bit converter, the least significant bit is 0.024% of full-scale.

Channels 1 and 2 of the Labmate system were set up to accept a full range input of ± 5 V with unity gain, an accuracy of 1.2 mV and a sampling period of about 1 second. Channel 1 measured the voltage difference associated with $(P_o - P_{c2})$, and channel 2 measured the voltage difference associated with $(P_{c1} - P_{c2})$. Channel 3 was set up to accept a full range input of ± 0.01 volts, an accuracy of $2.4 \mu\text{V}$ and a sampling period of about 1 second. Channel 3 measured the voltage difference associated with $(P_{c2} - P_s)$. Channel 4 was short-circuited for auto-zeroing purposes. The voltage measured across Channel 4 is automatically measured and subtracted from the other channels to account for zero drift of the Labmate system. The auto-zero value is updated every 60 seconds.

The static pressure distribution around the airfoil was provided by static taps located on the airfoil (see Section 3.1.2 for tap locations). These static taps were connected to a vertical manometer bank with PVC tubing and the manometer bank yielded pressure values in inches of water ($\pm 0.05''$ (1.25 mm)). P_{c2} was used as the reference pressure for the manometer bank readings.

3.2 Experimental Procedures

As mentioned earlier, three patch thicknesses were tested at three chordwise positions on the airfoil (see Section 3.1.3). The clean airfoil, without patches, was also tested. The data from this clean case is used as a benchmark during data comparison. For

each patch/position combination, the airfoil was tested at five angles of attack between zero-lift and just below stall conditions: 0.0, 1.0, 2.3, 3.4, and 4.1 degrees. At each angle of attack, the airfoil static pressure distribution and wake data were acquired (see Section 3.1.5) to provide lift and drag data. The processing of the data will be discussed in Section 3.2.3. During the preliminary stages of testing, the effects of the Reynolds number on the drag values were also investigated.

3.2.1 Calibration

Before wind tunnel testing commenced, the instrumentation and test section had to be calibrated to ensure accurate experimental results.

In order to determine voltage inputs to the instrumentation, outputs from the power supplies were verified with a digital voltmeter.

Before testing, the distance traversed by the traversing gear was verified with a micrometer (short distances) and a ruler (long distances). After each test run, the distance traversed by the Pitot-static probe was verified with a tape measure. It was determined that the traverse gear could lose approximately 0.1 mm over a 70 to 100 mm traverse.

As already mentioned, manometers connected in parallel with the pressure transducers were used to calibrate the transducers. Calibration of the pressure transducers was performed periodically throughout the testing. Illustrations of the transducer calibration are shown in Figures 3.11 a), b), and c). As shown, there is negligible scatter for the $(P_o - P_{c2})$ and $(P_{c1} - P_{c2})$ calibration curves. There is more scatter in the $(P_{c2} - P_s)$ calibration due to the very low values that had to be measured; slight tunnel fluctuations would have more of an impact on these low values.

Calibration of the pressure transducers were performed with the *trav.bas* and *calib.bas* programs which were written by Carnegie (1992) and modified by the author.

Figure 3.11: Pressure Transducer Calibrations

As seen in Appendix A.1, the *trav.bas* program obtained the voltage values from channel one ($P_o - P_{c2}$), then channel 2 ($P_{c1} - P_{c2}$), and finally channel 3 ($P_{c2} - P_s$) during each sample cycle. During calibration, the *trav.bas* program sampled a total of eleven voltages from each of the three channels, calculated the mean voltage value for each channel and interactively asked for the corresponding manometer reading. In Carnegie (1992), eight voltage values were sampled to calculate a mean value; however, the author chose to sample eleven voltage readings in order to be slightly more conservative. Transducer voltage values and manometer readings were obtained at approximately twelve points over the operating range of the wind tunnel. The mean transducer voltages and the manometer readings for ($P_o - P_{c2}$), ($P_{c1} - P_{c2}$), and ($P_{c2} - P_s$) were stored in a data file for later manipulation by the *calib.bas* program.

The *calib.bas* program read the transducer voltages and manometer readings from the *trav.bas* program data file and calculated a polynomial curve fit. As seen in Appendix A.2, the polynomial curve fit coefficients were calculated using the method of least squares and Gauss-Jordan elimination to reduce the matrix. It was determined by visual inspection that a linear curve fitted the transducer/manometer data for ($P_o - P_{c2}$) and ($P_{c1} - P_{c2}$) but a fifth order polynomial was needed for the ($P_{c2} - P_s$) data points. After the polynomial coefficients were calculated, they were stored in data files for later use. Transducer/manometer data was plotted against the calibration curves for a visual confirmation of the calculations. Figures similar to Figure 3.11 were generated twice a week to check for any transducer drift during experimentation.

During test runs, the *trav.bas* program also sampled a total of 11 voltages from each of the three channels, at each probe-unit position. The data acquisition system sampled voltages from each channel, i.e., a voltage was measured from channel 1, then channel 2, then channel 3, then channel 1, and so on. As mentioned earlier, the integration period of the Labmate Acquisition system is fixed at 33.33 milliseconds.

Figure 3.12: Comparison of Individual Voltage Samples and Corresponding Mean Voltage Values

Due to software routines such as auto-zeroing, and built-in time delays, each channel was sampled about once every three seconds and a total of 33 samples were collected over a 30 second time period. The eleven samples from each channel were then averaged by trav.bas and the average for each channel was recorded.

Figure 3.12 illustrates differences between individual samples of transducer voltages for the empty tunnel test section and the calculated mean voltages. It is a visual indication of the unsteadiness of the tunnel freestream. To obtain these readings, the Pitot tube was installed in the empty test section. The wind tunnel was set at approximately 60 m/s and six consecutive sets of $(P_o - P_{c2})$ and $(P_{t1} - P_{c2})$ (eight samples per set) were taken with the trav.bas program and the Sciometric System. Each set of eight samples was measured over a period of about 22 seconds, and due to the time taken to write down the measurements, about 3.5 minutes elapsed during the measurement of all 48 samples. Figure 3.12 illustrates the six sets of tests and the corresponding calculated mean value for each set of eight samples. The mean values showed a repeatability of approximately ± 0.01 volts. Figure 3.12 also shows

the average of all 48 samples. During further testing and calibration, 11 samples taken over a period of about 30 seconds were used to obtain one data point and as will be shown later in this section, this sampling practice was found to give suitable repeatability in drag coefficients ($\pm 1-2\%$).

Figure 3.13 illustrates spatial variation of static and dynamic pressures in the empty test section. Pressures were measured in the planes where the leading and trailing edges of the airfoil would be located after installation of the airfoil. Another plane of measurements was made at $0.6c$. The large dots in Figure 3.13 represent the measurement locations. The wind tunnel calibration constant, K , ($K = (P_{c1} - P_{c2})/(1/2\rho V^2)$), compares the difference in reference pressures to the test section's freestream dynamic pressure. Other conventional test sections used in the wind tunnel give a calibration constant of 0.91, whereas the test section used in this study gave a calibration constant of about 0.87 near the centre of the test section. As expected, the value for K decreases slightly, i.e., freestream velocity increases, towards the rear of the test section due to increasing boundary layer thickness at the test section walls. As seen in Figure 3.13, the value of K decreases by about 3% from the leading to trailing edge of the model airfoil position. Since K is a function of V^2 , the velocity only increases by about 1.73% from the leading to trailing edge of the airfoil. This variation will not have much of an impact on the experimental values for lift and drag coefficients, since lift is due to the pressure difference across the airfoil at any chordwise station and the drag is determined by the wake-traverse method which is only sensitive to the total and static pressure variation in the traverse plane. Assuming that freestream total pressure is constant, Bernoulli's equation requires that static pressure decrease if the dynamic pressure increases. Figure 3.13 illustrates the decrease in static pressure towards the rear of the test section. The measurements of $(P_s - P_{c2})/(P_{c1} - P_{c2})$ represent the static pressure variation.

All measurements taken in the vertical centreline plane of the test section

Plane 1: Corresponds to the Leading Edge of the airfoil. $K=0.8819 \pm 0.0031$

Plane 2: Corresponds to the 0.6% c of the airfoil. $K=0.8712 \pm 0.0037$

Plane 3: Corresponds to the Trailing Edge of the airfoil. $K=0.8516 \pm 0.0077$

Figure 3.13: Spatial Variation of Static and Dynamic Pressures Over 3 Cross Section Planes in the Empty Wind Tunnel Test Section (two sets of data). $K = (P_{c1} - P_{c2}) / (P_o - P_s)$

After the airfoil and the pressure tubing between the airfoil static taps and the manometer bank had been installed, the static taps were taped over and the height of the manometer bank reservoir was varied. This was done to check for air leaks in the tubing and connections. If the level of the manometer changed with the change in the reservoir height, a leak in the tubing system was revealed. As a result of this exercise, a few leaks were detected and repaired.

As mentioned in the Introduction, this study involved two-dimensional testing of a CF-18 airfoil. Part of the test section calibration was to ensure that the flow over the airfoil was indeed two-dimensional. A flow visualization method was used to check the two-dimensionality of flow over the airfoil at various angles of attack. A mixture of oil and paint pigment was applied in a thin layer to the leading third of the airfoil. The wind tunnel was brought up to speed for about a minute and the resulting pattern of the oil movement was examined. Any excess oil streaked towards the trailing edge and the streaks were always parallel to the tunnel walls. If a separation bubble was present at the leading edge of the airfoil, the chordwise position of the bubble's trailing edge was uniform across the span of the airfoil. The results of the flow visualization confirmed that the flow was two-dimensional. Flow visualization will also be discussed in Section 4.7.

Another test of two-dimensionality was comparing drag coefficients obtained from wake traverses at different spanwise positions behind the airfoil. Drag coefficients were measured when the Pitot-static probe was traversed in the mid-span plane and in planes 3" above and below the mid-span plane. As seen in Figure 3.14, the drag coefficients obtained when the probe was above and below the mid-span plane were within 2% of the C_d 's when the probe was aligned with the mid-span of the airfoil. This indicated that the flow near the mid-span of the airfoil was indeed two-dimensional.

Figure 3.14 also gives data for the drag coefficient at various Reynolds numbers.

Figure 3.14: C_d at Different Spanwise Positions and Reynolds Numbers Based on Chord Length of the Airfoil

During calibration and preliminary testing, it was noted that the drag coefficient remained constant at various Reynolds numbers for the same airfoil configuration: this was noted for various angles of attack and patch configurations. Since the C_d values were the same regardless of whether the tunnel was running at full speed or at 85% ($Re=2.35 \times 10^6$), the tunnel could be operated at the lower velocity in order to save wear and tear on the equipment. It may be noted that a Reynolds number of approximately 2.7×10^6 (based on chord length) is equivalent to the tunnel running at the full speed of roughly 75 m/s.

Another concern during tunnel testing is the effect of temperature on the data. Temperature differences can affect dynamic similarity of the tests since change in temperature changes the kinematic viscosity term of the Reynolds number. During consecutive running of three test runs, the air temperature in the tunnel could rise by 10–20°C between the first and third test. Figure 3.15 shows the wake plots from three consecutive test runs. The zero value on the x-axis of the figure corresponds to a point on a line that is parallel to the test section wall and intersects the trailing edge of the

Figure 3.15: Repeatability of Wake Plots

airfoil. The tunnel was not allowed to cool down between the tests. The first test was performed when the tunnel was at room temperature (22°C) and the tunnel air was about 40°C by the end of the third test run. As seen in Figure 3.15, the three wake plots overlay each other. The data points for the third test are in between the data points for the first and second test because the probe's starting point was staggered by 0.5 mm from the first two runs. The calculated drag coefficients for the three tests differed by an acceptable 1-2%.

In the early stages of testing, it was observed that the static tap pressure at the suction peak could change by up to 1 in.H₂O during a test run. This pressure change would take place over the course of one to ten minutes. At first, the author thought the pressure change would affect the drag data; however, the ratio $(P_{tap} - P_{c2})/(P_{c1} - P_{c2})$ was noted at various times during the pressure changes and the recorded ratio was found to remain constant during the pressure changes which indicated that the lift coefficient would remain constant during the pressure changes. In addition, plots

of wake data remained smooth and continuous during the pressure changes which indicated that the drag coefficient data was not affected. The pressure changes were essentially eliminated when a loose turning vane at the first corner downstream of the test section was repaired.

During calibration, tufts of yarn were glued to the airfoil slats on the slatted wall of the blockage-tolerant test section. The tufts gave a visual indication as to whether the flow remained attached to the airfoil slats. During calibration and testing, visual inspection of the tufts confirmed that the flow remained attached to the slats and they did not experience stall.

Tufts were also glued to the pressure and suction surfaces of the airfoil model. The tufts were always parallel to the floor of the test section which indicated two-dimensional flow. When the airfoil went beyond about $\alpha=3^\circ$, tufts located at the leading edge of the suction surface detached from the surface and started to point upstream at higher angles of attack which indicated an area of reverse flow.

3.2.2 Description of a Test Run

When calibration had been performed, it was time to progress through the test matrix which consisted of three patch shapes (2D, square and round), three patch thicknesses (thin, medium and thick), three chordwise positions ($x/c=0.06$, 0.25 and 0.50) and five angles of attack ($\alpha=0^\circ$, 1° , 2.3° , 3.4° and 4.1°). Each test run generally followed the process described below. Sample outputs from a test run are presented in Appendix B.

If a patch was required, it was installed in the appropriate location on the airfoil. Sewing needles were used to ensure that the static holes in the patches were aligned with the static holes on the airfoil. The Pitot and static probe unit was moved to its starting position; the Pitot and static probe unit was positioned in the spanwise direction by measuring to the centre of the Pitot tube mouth. As well, the airfoil was

set to the required angle of attack. The airfoil was positioned against angle of attack lines that were marked on the floor of the test section. The repeatability of the angle of attack measurement was ± 0.1 .

The program `trav.bas` was loaded into the QBasic environment on the data acquisition computer, and parameters such as traverse stepsize and traverse distance, were specified. At a low angle of attack the stepsize had to be fairly fine, because the wake was relatively narrow. At a higher angle of attack, the traverse stepsize could be coarser. After ensuring that the voltage supplies, Sciometric system, and the traversing motor were powered on, the `trav.bas` program was started. The `trav.bas` program verified the operation of the A/D system, measured the zero values from each channel, asked for some descriptive information, and then informed the operator to bring the tunnel up to speed and enable the traversing and data collection for the drag measurements. At each probe-unit position, the data acquisition system acquired 11 samples for each channel as mentioned in Section 3.2.1. Then the traverse gear moved the Pitot-static probe by the required distance, voltages were recorded at this next position, and so on. Refer to Section 3.1.5 for a description of the pressures measured by each A/D channel. When the traverse was finished, the voltage data from the A/D channels was stored in the `\trav\data` directory on the data acquisition computer.

While the drag data were being obtained, the lift data were obtained by manually reading the static tap pressures from the manometer bank. The manometer heights were entered into a text file for later analysis by computer.

3.2.3 Data Analysis

After the data were collected, they were analyzed to produce lift and drag coefficients, wake plots and plots of pressure coefficients. The drag and lift analysis programs are listed in Appendices A.3 and A.4, respectively. The results of the analysis will be

discussed in the next chapter. The actual process, equations and techniques utilized in the analysis will now be discussed, beginning with the drag analysis.

As mentioned earlier, the profile drag of the airfoil was determined by the wake traverse method. The principle of the wake traverse method is that the drag force must equal the momentum-flux deficit in the airfoil wake. The wake measurements were used to determine the momentum-flux deficit. From Pankhurst and Holder (1965), profile drag for incompressible flow is given by the expression:

$$C_d = \int C'_d d(y/c) \quad (3.1)$$

where

$$C'_d = 2\sqrt{q-p}(1-\sqrt{q}) \quad (3.2)$$

and where

$$q = \frac{P_{o_w} - P_{s_{fs}}}{P_{o_{fs}} - P_{s_{fs}}} \quad \text{and} \quad p = \frac{P_{s_w} - P_{s_{fs}}}{P_{o_{fs}} - P_{s_{fs}}} \quad (3.3)$$

P_o and P_s are total and static pressures, respectively, and the sub-subscripts fs and w indicate freestream and wake, respectively. As seen in the above equations, profile drag is primarily the integrated difference between the freestream momentum and the momentum of the fluid in the wake. From Equation 3.1, the incremental drag coefficient at a probe position can be written as:

$$\Delta C_d = C'_d \cdot \frac{\Delta y}{c} \quad (3.4)$$

where Δy is the traverse stepsize across the wake.

The data acquisition system measured voltages that represented $(P_o - P_{c2})$, $(P_{c1} - P_{c2})$, and $(P_{c2} - P_s)$. The first step of the drag analysis was to calculate pressure differences from the measured voltage values. The polynomial coefficients provided by the *calib.bas* program (see Section 3.2.1) were used to obtain pressure differences. For example, the $(P_o - P_{c2})$ and $(P_{c1} - P_{c2})$ calibrations provided polynomial coefficients for a linear equation, i.e., $y=mx+b$. The voltage values were substituted for the x -value of the equation and the pressure differences resulted.

Part of the data analysis involved converting the pressure differences into a form that could be used in Equation 3.3. As seen in Figure 3.15, pressure measurements from outside of the wake were relatively constant and were considered to be freestream measurements. A programmable method was needed to determine where the freestream ended and where the wake began. For each probe position, values were calculated for the ratio $Z = (P_o - P_s)/(P_{c1} - P_{c2})$ by summing the values $(P_o - P_{c2})$ and $(P_{c2} - P_s)$, then dividing by $(P_{c1} - P_{c2})$. Each value of Z was compared to the previous value of Z and if the difference between the two values was below a prescribed threshold (less than 0.5% of Z), that probe position was said to be in the freestream; otherwise, the probe position was in the wake. Although differences in the Z ratio behind the trailing edge of the airfoil could be less than the prescribed threshold (i.e., the bottom of the curves in Figure 3.14), the program did not designate that area as the edge of the wake. The algorithm was coded to err on the conservative side; for example, a probe position near the wake boundary was more likely to be considered a part of the wake rather than a part of the freestream.

Once the wake boundaries were determined, average values for $(P_{c2} - P_s)$ and Z were calculated on the outside of the wake boundaries and were used as freestream values. If the freestream values on either side of the wake differed, there was assumed to be a linear variation in the freestream values across the wake. The freestream values for $(P_{c2} - P_s)$ and Z were used to calculate the following at each probe position:

$$P_{s,w} - P_{s,fs} = (P_s - P_{c2})_w + (P_{c2} - P_s)_{fs} \quad (3.5)$$

$$P_{o,w} - P_{s,fs} = (P_o - P_{c2})_w + (P_{c2} - P_s)_{fs} \quad (3.6)$$

$$\text{and} \quad P_{o,fs} - P_{s,fs} = Z_{fs} \cdot (P_{c1} - P_{c2}) \quad (3.7)$$

where the subscript w refers to values measured when the probe unit was in the wake and the subscript fs refers to values measured when the probe unit was in the

freestream. It was assumed that $P_{c2f} - P_{c2w}$ was negligible. The values produced from the above equations were then used in Equation 3.3. Equation 3.7 was used instead of just $(P_o - P_{c2}) + (P_{c2} - P_s)$ in order to dampen out any fluctuations in $(P_{c1} - P_{c2})$.

Finally, Equation 3.4 was used to calculate ΔC_d at each probe position and the ΔC_d 's were summed to find the total C_d . The calculated C_d value was then stored in a text file. Values for probe position, $(P_o - P_{c2})/(P_{c1} - P_{c2})$, $(P_{c2} - P_s)/(P_{c1} - P_{c2})$ and Z were also stored in a text file for later reference.

The lift analysis program read in a text file that contained the angle of attack in degrees, atmospheric pressure, readings for P_{c1} and P_{c2} , and the static tap readings. All the pressure readings were recorded in inches of water. The static tap readings were recorded in the following order: the 17 taps of the top surface starting with the tap closest to the trailing edge; the leading edge tap; and the 15 taps of the bottom surface starting with the tap closest to the leading edge.

The lift analysis program also asked for freestream values of Z and $(P_{c2} - P_s)/(P_{c1} - P_{c2})$; these values were obtained from calculations of the drag analysis program. With these freestream ratios and the readings from the text file, the program was able to calculate the pressure coefficient at each tap as in the following equation:

$$C_p = \frac{P_{c2} - P_{tap}}{Z_{fs} \cdot (P_{c1} - P_{c2})} - \frac{((P_{c2} - P_s)/(P_{c1} - P_{c2}))_{fs}}{Z_{fs}} \quad (3.8)$$

Since there was no static tap at the very trailing edge of the airfoil, the trailing edge pressure coefficient was assumed to be an average of the closest tap on the bottom surface and the closest tap on the top surface. The pressure coefficients were stored in a text file for later reference.

Using the pressure coefficients at each tap, the normal and axial force coefficients were calculated with the following equations:

$$C_{n_i} = 0.5 \cdot (C_{p_{i+1}} + C_{p_i}) \cdot \left(\left(\frac{x}{c} \right)_{i+1} - \left(\frac{x}{c} \right)_i \right) \quad (3.9)$$

$$C_n = \sum_{i=0}^{33} C_{n,i} \quad (3.10)$$

$$C_{x,i} = 0.5 \cdot (C_{p,i+1} + C_{p,i}) \cdot \left(\left(\frac{y}{c} \right)_{i+1} - \left(\frac{y}{c} \right)_i \right) \quad (3.11)$$

$$C_x = \sum_{i=0}^{33} C_{x,i} \quad (3.12)$$

The normal and axial force coefficients were resolved into lift and drag coefficients with:

$$C_l = C_n \cdot \cos \alpha - C_x \cdot \sin \alpha \quad \text{and} \quad C_d = C_n \cdot \sin \alpha + C_x \cdot \cos \alpha \quad (3.13)$$

where C_n is the normal force coefficient and C_x is the axial force coefficient. The lift and drag coefficients were then stored in a text file for later reference. C_d was calculated from the force coefficients for comparison with the C_d value from the drag analysis. The accuracy of the lift coefficient calculations is limited by the density of the static tap distribution. If there are areas of pressure fluctuations and a low density of static taps, the lift coefficient will not be very accurate.

Measurements of spanwise variation of C_d for selected patch configurations were also carried out. A wake traverse was performed when the Pitot probe was aligned with the centreline plane of the patch. The traverse plane position was then moved spanwise in increments of approximately 0.25 times the patch width and a wake traverse was performed at each position. The probe was moved spanwise until the C_d measurement reached the clean airfoil value. Since the patches were symmetrical about the patch's mid-span, the C_d measurements across the half-span of the patch were mirrored across the mid-span plane of the patch.

The results of the testing and analysis will be discussed in the next chapter.

4. Results and Discussion

This chapter presents the results of the wind tunnel testing of the CF-18 airfoil model. First, a few of the experimental lift coefficients and pressure distributions for the clean airfoil are compared to computed coefficients and distributions. Next, experimental pressure distributions from various test configurations are presented and compared. Illustrations of how the patches affected the two dimensional lift curves of the airfoil follow the pressure distribution discussion. Examples of wake traverses are presented and discussed. Next, lift versus drag coefficient curves are presented and discussed. The drag and lift coefficient data are also presented in tabular form. Experimental results of variations in local drag coefficient across the width of selected patches are then presented. The final experimental results presented are photographs that resulted from flow visualization experiments. Then, the experimental results are compared to the computational results of Carnegie (1992). The chapter ends with a discussion regarding application of the experimental results to the full-scale airfoil.

4.1 Comparison to INVAFRF

As mentioned earlier, in Section 3.1.2, the INVAFRF software assumes two dimensional, inviscid, incompressible flow when calculating the lift coefficient and pressure distribution of an airfoil in an infinite freestream. Figure 4.1 compares INVAFRF calculated pressure distributions to experimental pressure distributions for a clean CF-18 airfoil. The airfoil coordinates used by INVAFRF corresponded to the coordinates of the static taps on the airfoil surface. As seen in Figure 4.1, the experimental and calculated pressure coefficients on the suction surface agree well at low angles of

Figure 4.1: Comparison of Computed and Experimental C_p 's for the Clean CF-18 Airfoil at $\alpha=2.3^\circ$ and 4.1°

Figure 4.2: Comparison of Computed and Experimental C_l 's for the Clean CF-18 Airfoil

attack while the experimental pressure coefficients on the pressure side and the lift coefficients were usually somewhat larger in magnitude than the coefficients calculated by INVAIRF. One would expect that the lift coefficients calculated by INVAIRF would be higher than the experimental since INVAIRF assumes inviscid flow and it is somewhat surprising to see the opposite behaviour here. Since the experimental C_p values on the pressure side are higher, it may be that the experimental results suffer from slight blockage effects, i.e., compared to the infinite freestream case there is less flow around the pressure side of the airfoil due to the proximity of the solid wall. In Figure 4.1 b) at $\alpha=4.1^\circ$, there is poor agreement between experimental and computational pressure coefficients in the vicinity of the leading edge suction peak. This disagreement is attributed to the low Reynolds numbers of the experiments which clearly results in the presence of a fairly large laminar-separation bubble at this angle of attack. At full scale Re , the separation bubble would most likely be either extremely short or not occur at all and the suction peak would be much larger in magnitude,

similar to the INVAIRF results.

Figure 4.2 shows that experimental lift coefficients for the clean airfoil were higher than the calculated C_l 's by about 0.04–0.05. In terms of the lift curve slope, the experimental and computational results agree well. The linear part of the experimental lift curve has the same slope as INVAIRF's lift curve until approximately $\alpha=4.5^\circ$, where the experimental lift curve starts levelling off. It may be noted that the experimental lift coefficients at 5° and above may be in slight error since the airfoil begins to block a large percentage of the wind tunnel cross-section.

The agreement of experimental and computational results in Figures 4.1 and 4.2 (for $\alpha \leq 3^\circ$) indicates that tunnel wall effects are relatively small. Since the measured pressure distributions are similar to those computed for an airfoil in an infinite freestream, the measured effects of patches should not be significantly affected by wall interference effects. More problematic is the effect of the low experimental Reynolds number at the higher angles of attack ($\alpha \geq 3^\circ$). As will be seen, some of the results were substantially affected by the presence of relatively large laminar-separation bubbles at the higher angles of attack.

4.2 Experimental Pressure Distributions

Figures 4.3 through 4.7 show additional examples of pressure distributions around the airfoil. Figure 4.3 compares pressure distributions at five different angles of attack for the clean airfoil. There was a sharp suction peak at the leading edge of the airfoil at 2.3° which led to a strong adverse pressure gradient downstream of the peak. The height of the suction peak decreased and the suction peak became relatively flat as the angle of attack was increased beyond 2.3° . The lack of a sharp suction peak for $\alpha \geq 3^\circ$ indicates a relatively long leading edge separation bubble which is characteristic of thin airfoils at low Reynolds numbers. Figure 4.3 also illustrates that the magnitude

Figure 4.3: Pressure Distributions at Various Angles of Attack for the Clean Airfoil; $Re \approx 2.4 \times 10^6$

of the favorable pressure gradient at the leading edge of the pressure surface decreased as the angle of attack (AOA) was increased.

Figure 4.4 illustrates typical pressure distributions for a test configuration that included a round thick patch located at $x/c=0.25$. The pressure distribution illustrates the pressure increase in front of the patch which tends to produce local separation and flow reversal in front of the patch. The flow over the patch had a higher suction pressure than on the surrounding airfoil surface.

Figure 4.5 shows how the three different patch thicknesses affect the pressure distribution at an angle of attack of 3.4° when placed at a chordwise position of $x/c=0.06$. Figure 4.5 concentrates on one portion of the pressure distribution because the remainder of the distribution was practically identical for all three patch thicknesses. The plot illustrates that the suction pressure decreased in front of and behind the patch, and that the suction pressure increased over the patch surface as the

Figure 4.4: Typical Pressure Distribution for a Thick Round Patch at $x/c=0.25$, $\alpha=0^\circ$ to 4.1°

Figure 4.5: Comparison of C_p Distributions for Different Thicknesses of a Square Patch at $x/c=0.06$, $\alpha=3.4^\circ$

Figure 4.6: Comparison of C_p Distributions for Different Thicknesses of a 2D Patch at $x/c=0.06$, $\alpha=1^\circ$

Figure 4.7: Comparison of C_p Distributions for a 2D Medium Patch at Various Chordwise Positions; $\alpha=2.3^\circ$

patch thickness increased. A large suction peak was recorded near the leading edge of the airfoil when the thick patch was applied. This suction peak was also present for $\alpha=3.4^\circ$ when the thick 2D and thick round patches were applied at $x/c=0.06$. Pressure spikes could be present at other points on the patch and airfoil surfaces, but they were undetectable since the static taps were located at finite, discrete points on the surfaces.

Figure 4.6 presents pressure distribution changes when 2D patches of three different thicknesses are placed at $x/c=0.06$ for an AOA of 1° . Again, as per Figure 4.5, only a small portion of the pressure distribution is illustrated. In comparison to the pressure distributions at a higher angle of attack (see Figure 4.5), patches at a low angle of attack resulted in a larger change in the pressure distribution relative to the clean airfoil condition at the same AOA.

Figure 4.7 compares pressure distributions for a 2D medium patch at the three different chordwise positions at $\alpha=2.3^\circ$. The pressure distributions illustrate the pressure increases in front of and behind the patch and the suction increases over the patch's surface. Examination of available C_p points indicates that ΔC_p between the patch surface and the clean airfoil was about the same for all chordwise positions of the patches. Comparing Figures 4.5 and 4.7 reveals that the pressure increase in front of a patch was not as great at $\alpha=3.4^\circ$ as at $\alpha=2.3^\circ$.

4.3 Lift Curves

Illustrations of how the patches affected the lift curve of the airfoil are presented in Figures 4.8 to 4.10. Lift curves for the thin patches were not included since the lift values for thin patches were practically identical to the lift curve for the clean airfoil. Generally, the following statements can be made:

Figure 4.8: C_l vs α : 2D Medium and Thick Patches

a) Medium patches

d) Square thick patches

b) Thick patches

Figure 4.9: C_l vs α : Square Medium and Thick Patches

a) Medium patches

b) Thick patches

Figure 4.10: C_l vs α : Round Medium and Thick Patches

- For patches of the same thickness, the C_l loss was greatest for the 2D patches, followed by the square patches and then the round patches. Recall that C_l is the coefficient of lift *per unit span*.
- C_l loss was greatest for patches at $x/c=0.50$ followed by patches at $x/c=0.25$ and then patches at $x/c=0.06$.

Lift coefficient values for the 25% c and 50% c chordwise positions will not be as accurate as lift coefficients for the 6% c position. Since the lift coefficients were calculated from the pressure distributions, any sharp fluctuations in the distribution would lead to accurate lift coefficients only if there were a high concentration of static taps in the area of fluctuation. For example, in Figure 4.7, a pressure fluctuation near $x/c=0.50$ influences a large section of x/c because there are few static taps in the vicinity. On the other hand, a fluctuation of similar magnitude near $x/c=0.06$ influences a small section of x/c since there are more static taps in the area.

The reductions in C_l seen in Figures 4.8 to 4.10 are generally modest. As mentioned above, the reductions were larger for patches located farther aft on the suction surface. This trend may not apply to airfoils whose suction peak is broader and/or occurs farther aft than that of the CF-18 airfoil.

4.4 Wake Profiles

Examples of wake profiles from the centreline plane of the patches are illustrated in Figures 4.11 through 4.14. The dynamic pressure was normalized by the difference in reference pressures and plotted against the probe position. A negative probe position indicates that the probe was downstream of the suction side of the airfoil. The zero probe position is directly downstream of the trailing edge of the airfoil, i.e., a line joining the trailing edge of the airfoil and the zero probe position is parallel to the

sidewalls of the test section. The area above the wake profile curves is proportional to the drag coefficient calculated. Figure 4.11 shows differences in wake profiles for a thick square patch configuration as the angle of attack was changed. At 0° , the wake was relatively narrow and fairly deep. The wake was broader, but shallower, at 1° and the wake widens and deepens as α is increased.

Figure 4.12 compares wake profiles of configurations where the chordwise position, AOA, and patch shape were constant, but the thickness of the patch was varied. Figure 4.12 clearly shows the change in wake shape due to the change in patch thickness, since the patch's wake on the pressure side of the airfoil was very similar to the shape of the clean airfoil's wake. The wake with the thin patch was fairly similar to the wake of the clean airfoil which reflects the finding that C_d values for the thin patches were not much larger than those for a clean airfoil. As the patch thickness was increased, the wake broadened on the suction side of the airfoil and deepened slightly. The thicker patches created higher momentum loss and higher drag than the thinner patches.

In Figure 4.13, wake profiles for different patch shapes of the same thickness, chordwise position and AOA are compared. Again, the wakes on the pressure side of the airfoil were similar to the clean airfoil case, so the changes in wake profile were indicative of changes in patch shape. The wakes in the centreline planes of the square and round patches were very similar, while the 2D wake profile was slightly wider.

Figure 4.14 shows the effect of placing a patch at different chordwise positions. The wake profiles of a 2D medium patch are illustrated and compared to the clean airfoil wake profile. The wake profiles at $x/c=0.25$ and $x/c=0.50$ were very similar. The wake profile at $x/c=0.06$ indicates that the drag coefficient at this chordwise position was higher than at the other chordwise positions. Recall, however, that the largest reduction in C_l did not occur at this position.

Figure 4.11: Typical Wake Profiles at Patch Centreline for a Thick Square Patch Configuration at $\alpha=0^\circ, 1^\circ, 2.3^\circ, 3.4^\circ, 4.1^\circ$; $x/c=0.06$

Figure 4.12: Wake Profiles at Patch Centreline for Square Patches of Different Thicknesses; $x/c=0.06$, $\alpha=1^\circ$

Figure 4.13: Wake Profile Comparisons at Patch Centreline for Medium Patches of Different Shapes; $x/c=0.06$, $\alpha=1^\circ$

Figure 4.14: Wake Profile Comparisons at Patch Centreline for a 2D Medium Patch at Different Chordwise Positions; $\alpha=1^\circ$

4.5 Drag Polar Results

C_l versus C_d data for various patch configurations is presented in Figures 4.15 to 4.20. Note that C_l and C_d are coefficients of lift per unit span and drag per unit span, respectively. In the case of square and round patches, C_l and C_d will vary with spanwise position. The data in Figures 4.15 to 4.20 are for the spanwise position at, or very near, the centreline of the patch. Figures 4.15, 4.16 and 4.17 show each patch at different chordwise positions while Figures 4.18, 4.19 and 4.20 compare different shaped patches, of the same thickness, at each chordwise position. All drag polar plots include the drag polar of the clean airfoil as a reference.

The reader may notice that there is no lift or drag coefficient data for the thin round patch. During testing of the thin 2D and square patches, it was noted that the C_l versus C_d curves for these two thin patches were virtually identical, and were very similar to the clean drag polar plot; therefore, it was decided to exclude the thin round patch from testing, since it would provide information very similar to the other thin patches.

The following general comments can be made about the C_l vs C_d plots:

- the lowest C_d is found at $\alpha=1^\circ$ for both the clean and patched airfoil;
- the highest increases in C_d , due to a patch, were seen at $\alpha=0^\circ$;
- patches at $x/c=0.06$ produced higher drag increments than similar patches at $x/c=0.25$ and 0.50 ;
- patches of the same thickness at $x/c=0.25$ and 0.50 produced very similar drag polars;
- the presence of a patch usually increased drag and decreased the lift coefficient.

The effect of patches at $x/c=0.06$ on drag coefficient at higher angles of attack is surprising. As illustrated in Figures 4.18 a), 4.19 a), and 4.20 a), at relatively high angles of attack, patches at 6% chord actually resulted in lower drag coefficients than those of the clean airfoil. This decrease-in-drag phenomenon was greater for the 2D and square patches than for the round patches, and greater for thicker patches. A tentative explanation for this phenomenon is as follows. At the higher angles of attack, at which the phenomenon occurs, the flow appears to separate upstream of the patch due to the strong adverse pressure gradient that would otherwise occur downstream of the airfoil's suction peak (this is the origin of the laminar-separation bubble that was discussed in Sections 4.1 and 4.2). The flow reattaches to the surface of the patch at or near its leading edge and the static pressure on the upstream-face of the patch is relatively low. There is consequently a suction force on this face of the patch, the suction force being larger for thicker patches. This suction force is responsible for the lower drag on the airfoil. The relatively low static pressure on the front face of the medium and thick patch is evident in Figure 4.5. Conversely, at lower angles of attack there is only a local separation directly in front of the patch, caused by the patch itself, and there is a high static pressure on the upstream face of the patch.

The C_l and C_d are also presented in Table 4.1. Lift and drag ratios are also presented. To arrive at the lift and drag ratios, the lift or drag coefficient from each test configuration was divided by the coefficient from the clean airfoil configuration.

Figure 4.15: C_l vs C_d at Patch Centreline. Comparisons for 2D Patches at Various Chordwise Positions. Data Points are for $\alpha=0^\circ, 1^\circ, 2.3^\circ, 3.4^\circ, 4.1^\circ$

Figure 4.16: C_l vs C_d at Patch Centreline. Comparisons for Square Patches at Various Chordwise Positions. Data Points are for $\alpha = 0^\circ, 1^\circ, 2.3^\circ, 3.4^\circ, 4.1^\circ$

Figure 4.17: C_l vs C_d at Patch Centreline. Comparisons for Round Patches at Different Chordwise Positions. Data Points are for $\alpha=0^\circ, 1^\circ, 2.3^\circ, 3.4^\circ, 4.1^\circ$

Figure 4.18: C_l vs C_d at Patch Centreline. Comparison for 2D & Square Thin Patches at Various Chordwise Positions. Data Points are for $\alpha=0^\circ, 1^\circ, 2.3^\circ, 3.4^\circ, 4.1^\circ$

Figure 4.19: C_l vs C_d at Patch Centreline. Comparison for 2D, Square & Round Medium Patches at Various Chordwise Positions. Data Points are for $\alpha=0^\circ, 1^\circ, 2.3^\circ, 3.4^\circ, 4.1^\circ$

Figure 4.20: C_l vs C_d at Patch Centreline. Comparison for 2D, Square & Round Thick Patches at Various Chordwise Positions. Data Points are for $\alpha=0^\circ, 1^\circ, 2.3^\circ, 3.4^\circ, 4.1^\circ$

Table 4.1: Lift and Drag Coefficients and Coefficient Ratios

SHAPE	THICKNESS	x/c	α (°)	C_l	C_d	COEFFICIENT RATIOS C_{lp}/C_{lc} C_{dp}/C_{dl}			
Clean Airfoil			0.0	0.0177	0.005464				
			0.0	0.0184	0.005350				
			0.0	0.0329	0.005461				
			1.0	0.1484	0.004339				
			1.0	0.1492	0.004260				
			2.3	0.2934	0.006073				
			2.3	0.2934	0.006154				
			3.4	0.4189	0.01259				
			3.4	0.4207	0.01263				
			4.1	0.5036	0.02176				
4.1	0.5049	0.02162							
2D	thin	0.06	0.0	0.0198	0.007558	0.86	1.39		
			0.0	0.0232	0.007414	1.00	1.37		
			1.0	0.1405	0.005423	0.94	1.26		
			2.3	0.2847	0.006317	0.97	1.03		
			3.4	0.4221	0.01311	1.01	1.04		
			3.4	0.4282	0.01342	1.02	1.06		
			4.1	0.4864	0.01878	0.96	0.87		
		0.25	0.0	0.0276	0.006953	1.20	1.28		
			1.0	0.1514	0.004859	1.02	1.13		
			2.3	0.2876	0.006455	0.98	1.06		
			3.4	0.4212	0.01358	1.00	1.08		
			4.1	0.4900	0.02083	0.97	0.96		
			4.1	0.4918	0.02048	0.98	0.94		
		0.50	0.0	0.0330	0.006022	1.43	1.11		
			0.0	0.0330	0.006222	1.43	1.15		
			1.0	0.1338	0.004831	0.90	1.12		
			2.3	0.2868	0.006462	0.98	1.06		
			3.4	0.4196	0.01352	1.00	1.07		
			4.1	0.4863	0.02166	0.96	1.00		
		2D	medium	0.06	0.0	0.0182	0.008512	0.79	1.57
					1.0	0.1460	0.007464	0.98	1.74
					2.3	0.2786	0.008181	0.95	1.34
					3.4	0.4199	0.01364	1.00	1.08
					4.1	0.4971	0.01758	0.99	0.81
					4.1	0.5078	0.01810	1.01	0.83

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SHAPE	THICKNESS	x/c	α	C_l	C_d	C_{l_p}/C_{l_e}	C_{d_p}/C_{d_e}
2D	medium	0.25	0.0	0.0212	0.007797	0.92	1.44
			1.0	0.1357	0.006254	0.91	1.45
			2.3	0.2783	0.007383	0.95	1.21
			3.4	0.4091	0.01465	0.97	1.16
			4.1	0.4882	0.02209	0.97	1.02
		0.50	0.0	0.0105	0.007468	0.46	1.38
			1.0	0.1197	0.005607	0.80	1.30
			2.3	0.2797	0.007297	0.95	1.19
			3.4	0.4032	0.01416	0.96	1.12
			4.1	0.4809	0.02213	0.95	1.02
			4.1	0.4850	0.02237	0.96	1.03
	thick	0.06	0.0	0.0105	0.01124	0.46	2.07
			1.0	0.1235	0.01109	0.83	2.58
			2.3	0.2815	0.01196	0.96	1.96
			3.4	0.4343	0.01433	1.03	1.14
			4.1	0.5155	0.01662	1.02	0.77
		0.25	0.0	0.0001	0.01097	0.00	2.02
			1.0	0.1074	0.009822	0.72	2.28
			2.3	0.2606	0.01005	0.89	1.64
			3.4	0.3916	0.01669	0.93	1.32
			4.1	0.4689	0.02354	0.93	1.09
		0.50	0.0	-0.022129	0.010125	-0.96	1.87
			1.0	0.106723	0.007952	0.72	1.85
			2.3	0.251209	0.009243	0.86	1.51
			3.4	0.386862	0.016325	0.92	1.29
			4.1	0.461732	0.023622	0.92	1.09
Square	thin	0.06	0.0	0.0375	0.007603	1.63	1.40
			1.0	0.1414	0.005243	0.95	1.22
			2.3	0.2904	0.006208	0.99	1.02
			3.4	0.4233	0.01273	1.01	1.01
			3.4	0.4251	0.01284	1.01	1.02
			4.1	0.4892	0.02015	0.97	0.93
		0.25	0.0	0.0281	0.006450	1.22	1.19
			1.0	0.1429	0.004833	0.96	1.12
			2.3	0.2947	0.006163	1.00	1.01
			3.4	0.4292	0.01433	1.02	1.14
			4.1	0.4877	0.02008	0.97	0.93

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SHAPE	THICKNESS	x/c	α	C_l	C_d	C_{l_p}/C_{l_c}	C_{d_p}/C_{d_c}
Square	thin	0.50	0.0	0.0116	0.005945	0.50	1.10
			1.0	0.1468	0.004620	0.99	1.07
			2.3	0.2938	0.006252	1.00	1.02
			3.4	0.4197	0.01332	1.00	1.06
			4.1	0.4916	0.02134	0.97	0.98
Square	medium	0.06	0.0	0.0328	0.008949	1.43	1.65
			1.0	0.1448	0.007167	0.97	1.67
			2.3	0.2816	0.007919	0.96	1.30
			3.4	0.4148	0.01249	0.99	0.99
			4.1	0.4885	0.01960	0.97	0.90
		0.25	0.0	0.0296	0.007675	1.29	1.41
			1.0	0.1390	0.006019	0.93	1.40
			2.3	0.2817	0.006960	0.96	1.14
			3.4	0.4178	0.01413	1.00	1.12
			4.1	0.4930	0.02100	0.98	0.97
		0.50	0.0	0.0203	0.007009	0.88	1.29
			1.0	0.1197	0.005669	0.80	1.32
			2.3	0.2832	0.006875	0.97	1.12
			3.4	0.4135	0.01461	0.98	1.16
			4.1	0.4866	0.02105	0.96	0.97
Square	thick	0.06	0.0	0.0058	0.01036	0.25	1.91
			1.0	0.1184	0.009793	0.80	2.28
			2.3	0.2658	0.009839	0.91	1.61
			3.4	0.4215	0.01284	1.00	1.02
			4.1	0.4973	0.02028	0.99	0.93
		0.25	0.0	0.0152	0.01150	0.66	2.12
			1.0	0.1141	0.009252	0.77	2.15
			2.3	0.2630	0.009677	0.90	1.58
			3.4	0.4013	0.01572	0.96	1.25
			4.1	0.4738	0.02177	0.94	1.00
		0.50	0.0	-0.0029	0.01087	-0.13	2.00
			1.0	0.1090	0.008724	0.73	2.03
			2.3	0.2653	0.009420	0.90	1.54
			3.4	0.3939	0.01625	0.94	1.29
			4.1	0.4664	0.02238	0.92	1.03

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SHAPE	THICKNESS	x/c	α	C_l	C_d	C_{l_p}/C_{l_c}	C_{d_p}/C_{d_c}
Round	medium	0.06	0.0	0.0286	0.008350	1.24	1.54
			0.0	0.0308	0.008607	1.34	1.59
			1.0	0.1273	0.006704	0.86	1.56
			1.0	0.1275	0.006935	0.86	1.61
			2.3	0.2522	0.007406	0.86	1.21
			3.4	0.4107	0.01294	0.97	1.03
			3.4	0.4085	0.01275	0.97	1.01
			4.1	0.4973	0.01996	0.99	0.92
			4.1	0.4920	0.01975	0.98	0.91
		0.25	0.0	0.0325	0.009823	1.41	1.81
			1.0	0.1379	0.007198	0.93	1.67
			2.3	0.2950	0.008135	1.01	1.33
			3.4	0.4195	0.01421	1.00	1.13
			4.1	0.4917	0.02170	0.98	1.00
		0.50	0.0	0.0428	0.009369	1.86	1.73
			1.0	0.1362	0.007561	0.92	1.76
			2.3	0.2905	0.008597	0.99	1.41
			3	0.4208	0.01429	1.00	1.13
			4.1	0.4915	0.02169	0.97	1.00
	thick	0.06	0.0	0.0333	0.01040	1.45	1.92
			1.0	0.1333	0.006498	0.90	1.51
			2.3	0.2822	0.005802	0.96	0.95
			3.4	0.4139	0.01282	0.99	1.02
			4.1	0.4767	0.01920	0.95	0.89
		0.25	0.0	0.0297	0.008802	1.29	1.62
			1.0	0.1320	0.006805	0.89	1.58
			2.3	0.2777	0.006863	0.95	1.12
			3.4	0.4153	0.01530	0.99	1.21
			4.1	0.4739	0.02191	0.94	1.01
		0.50	0.0	0.0236	0.006108	1.03	1.13
			1.0	0.1290	0.005087	0.87	1.18
			2.3	0.2733	0.006590	0.93	1.08
			3.4	0.4089	0.01522	0.97	1.21
			4.1	0.4862	0.02269	0.96	1.05

4.6 Spanwise Wake Measurements

As mentioned at the end of Section 3.2.3 (see page 40), the wakes of certain patch configurations were also traversed in planes at various spanwise distances from the plane of the patch centreline in order to investigate the spanwise variation of C_d . Results of the spanwise C_d measurements for square and round medium patches at $x/c=0.06$ are shown in Figure 4.21. Figure 4.22 illustrates the spanwise drag measurements for a square medium patch at $x/c=0.50$. The zero value of the spanwise probe position indicates that the Pitot probe was in the plane of the patch's centreline. The edges of the patch fall on the ± 1 probe position, since the probe position has been normalized against the semi-patch width. The measured C_d values are shown on the plots by X and triangle markers. The C_d plots at negative values of the probe position are simply the measured C_d values mirrored across the patch's centreline.

Patches of medium thickness were chosen for the spanwise C_d measurements because they were “middle of the road” patches. Square and round medium patches were tested to examine the effects of patch shape on the spanwise C_d measurements. Angles of attack of 1° and 2.3° at the 6% chordwise positions were tested since these configurations resulted in the greatest drag increase above the clean airfoil values (see Figures 4.15 and 4.16) at a positive AOA. The square medium patch, $x/c=0.50$, $\alpha=1^\circ$ configuration was also tested to investigate whether the spanwise drag distribution was similar at different chordwise positions.

As illustrated, the C_d values behind the outer edges of patches were lower than C_d values outboard of the patches. The drag coefficients outboard of the round patch were relatively higher than those outboard of the square patch. Figure 4.21 would suggest that the vortices (see Section 4.7 for evidence of the vortices) along the edge of the round patch are stronger than those along the square patch. The vortices convect more freestream fluid towards the centreline plane of the round patch, thus reducing

Figure 4.21: Spanwise Variation of C_d for Square and Round Medium Patches at $x/c=0.06$, $\alpha=1^\circ$ and 2.3° . ($C_d \equiv$ Local Drag Coefficient per Unit Span)

Figure 4.22: Spanwise Variation of C_d for a Square Medium Patch at $x/c=0.50$. $\alpha=1^\circ$. ($C_d \equiv$ Local Drag Coefficient per Unit Span)

Table 4.2: Summary of Effective Patch Width Calculations

PATCH & FIGURE REFERENCE	CLEAN C_d	AREA UNDER CURVE	(CENTRELINE C_d) - (CLEAN C_d)	w_{eff}
Round medium, $x/c=0.06$, $\alpha=1^\circ$. Figure 4.21a)	0.0040 0.0043	0.00791 0.00644	0.00253 0.00223	1.504
Square medium, $x/c=0.06$, $\alpha=1^\circ$. Figure 4.21a)	0.0041 0.0043	0.00742 0.00654	0.00344 0.00324	1.045
Round medium, $x/c=0.06$, $\alpha=2.3^\circ$. Figure 4.21b)	0.0062 0.0061	0.00337 0.00390	0.0009 0.0010	1.913
Square medium, $x/c=0.06$, $\alpha=2.3^\circ$. Figure 4.21b)	0.00605 0.0061	0.00409 0.00382	0.00164 0.00159	1.228
Square medium, $x/c=0.50$, $\alpha=1^\circ$. Figure 4.22	0.00397 0.0043	0.0039 0.00255	0.00195 0.00162	0.894

the momentum loss and drag in that plane.

Table 4.2 summarizes the results for effective patch width. The concept of effective patch width, w_{eff} , is illustrated in Figure 4.22. In Figure 4.22, the area between the clean airfoil C_d value and the spanwise C_d curve represents the drag increment, ΔC_D , due to the patch. The effective patch width is an aid to calculating the drag increment as seen in the following equation:

$$\Delta C_D = w_{\text{eff}} \cdot (\text{patch diameter or width}) \cdot (\text{centerline } C_d) \quad (4.1)$$

where the units of w_{eff} are $1/(\text{patch diameter or width})$. The effective patch width was calculated in the following manner. The area under the spanwise drag curve was determined by plotting the curves on finely incremented graph paper; the clean airfoil's C_d value was taken as the zero baseline for finding the area under the curve. The clean airfoil C_d was subtracted from the centreline C_d value and the area found above was divided by this difference. The solution of the division was twice the effective patch width. The area under the effective patch's spanwise drag curve is equivalent to the area under the measured spanwise drag curve.

As seen in Table 4.2, there were two values used for the clean C_d baseline. One value was from Table 4.1 and the other value was directly from the spanwise C_d

measurements. Both values were used to calculate w_{eff} . The values were generally within ± 0.1 of each other. The mean of the two values is given in Table 4.2.

As in Equation 4.1, the effective patch width can be used to find the incremental drag force caused by a patch. For instance, a round patch of medium thickness has been installed at $x/c=0.06$ and the aircraft is cruising at $\alpha=2.3^\circ$. It is known that the clean airfoil drag coefficient is 0.0062 and $C_d=0.0071$ along the centreline of the patch. Since $w_{\text{eff}}=1.875$, the drag coefficient value of 0.0071 can be applied along a section of span that is 1.875 times larger than the diameter of the patch. $C_d=0.0062$ is applied to the remainder of the wing span.

When comparing round and square patches, Table 4.2 shows that round patches have a larger effect on the overall drag since the effective patch widths are much larger for round patches.

4.7 Flow Visualization

Illustrations of oil-film flow visualization are shown in Figures 4.23 to 4.30. The photographs are approximately 60–70% of actual size. Square and round medium patches at $x/c=0.06$ were subjected to flow visualization testing. Sludge from a mixture of summer-grade chainsaw oil, 5W30 motor oil and black paint pigment was used as the oil application and this mixture was uniformly spread over the leading 25% of the airfoil surface. The tunnel was operated at about 70 m/s freestream velocity for 1–2 minutes at each test configuration. It should be noted that accumulations of excess oil ran towards the right side of the photos (bottom of the test section) since the airfoil was in a vertical plane. The flow of excess oil is most notable in Figure 4.23. Thin tape was used to cover the static tap holes during flow visualization tests. The tape was applied across the span of the airfoil in order to maintain a constant airfoil thickness across the span. A few imperfections in the flow visualization were due to

air bubbles under the tape, or joints between the tape strips.

Figures 4.23 and 4.28 illustrate flow over the patches at low angles of attack, i.e., 0° and 1° . The clear area at the leading edge of the airfoil indicates the laminar attached flow regime. Areas outboard of the patch are illustrative of flow over a clean airfoil. The clear areas immediately in front of and to the side of the patches illustrate the influence of a horseshoe vortex around the patch. A large difference between the flow over square and round patches can be seen behind the patches. Square patches have a uniform line of oil behind the patch while round patches have a line of oil that develops into a tail behind the centreline of the patch. The line of oil behind the patch shows the approximate point of reattachment after the flow separation from the top of the patch at its trailing edge. Figure 4.28 also shows that the flow on top of the patch tends to sweep outward towards the spanwise edges of the patch as the flow nears the trailing edge. This comparison of Figures 4.23 and 4.28 indicates that spanwise edges of square patches have a relative local influence on the flow pattern when compared to the spanwise edges of round patches.

Flow over the patches at $\alpha=2.3^\circ$ are shown in Figures 4.24 and 4.29. Along the leading edge of the airfoil is a uniform, thin strip of oil which is evident of a short separation bubble. The thin strip of oil is a visual confirmation of the pressure distribution evidence at an AOA of 2.3° (see Section 4.2). In Figure 4.24, the separation bubble at the leading edge of the patch can also be seen. Figure 4.24 clearly shows how the flow in front of the patch moves towards the outer edges of the patch to become part of the horseshoe vortex.

The change in flow over the leading edge of the airfoil with increased angle of attack can be seen when comparing Figures 4.24 ($\alpha=2.3^\circ$) and 4.25 ($\alpha=3.4^\circ$). The area of separation has lengthened to cover a larger percentage of the chord length. There appear to be larger shear stresses on the patch surface at the 3.4° AOA than

Figure 4.23: Flow Visualization: Square Medium Patch, $x/c=0.06$, $\alpha=1^\circ$

Figure 4.24: Flow Visualization: Square Medium Patch, $x/c=0.06$, $\alpha=2.3^\circ$

Figure 4.25: Flow Visualization: Square Medium Patch, $x/c=0.06$, $\alpha=3.4^\circ$

Figure 4.26: Flow Visualization: Square Medium Patch, $x/c=0.06$, $\alpha=3.6^\circ$

Figure 4.27: Flow Visualization: Square Medium Patch, $x/c=0.06$, $\alpha=4.1^\circ$

Figure 4.28: Flow Visualization: Round Medium Patch, $x/c=0.06$, $\alpha=0^\circ$

Figure 4.29: Flow Visualization: Round Medium Patch, $x/c=0.06$, $\alpha=2.3^\circ$

Figure 4.30: Flow Visualization: Round Medium Patch, $x/c=0.06$, $\alpha=4.1^\circ$

at 2.3° AOA which is evident from the lack of oil on the patch surface in Figure 4.25. At $\alpha=2.3^\circ$, reattachment is immediately after the leading edge, while at $\alpha=3.4^\circ$, reattachment is at approximately $6.5\%c$. The flow visualization photographs illustrate a smaller oil accumulation at the leading edge of the square patch when the AOA was 3.4° and above.

When comparing Figure 4.26 ($\alpha=3.6^\circ$) to Figures 4.27 ($\alpha=4.1^\circ$) and 4.30 ($\alpha=4.1^\circ$), it can be seen that the reattachment line is located at a higher chordwise position as the AOA is increased. In Figure 4.26, the reattachment line is located at approximately $7\%c$, while in Figures 4.27 and 4.30, the reattachment line is at approximately $9.6\%c$. In Figures 4.26, 4.27 and 4.30, the area upstream of the patch is clear of oil (high shear stress). In essence, the leading edge of the patch has become a backward-facing step due to the reverse flow at these angles of attack. Flow reversal was also noted when tufts of yarn were attached to the airfoil (see the end of Section 3.2.1).

As illustrated in Figures 4.27 and 4.30, the presence of the patch moved the reattachment line slightly forward when compared to the clean airfoil on either side of the patch. The earlier reattachment was partly due to the fact that the patch surface was higher than the clean airfoil, so the reattached flow would intersect with the patch surface before the surface of the clean airfoil.

In Figures 4.27 and 4.30, the oil pattern indicates there is some swirling motion in the bottom right corner of the photo. This flow pattern is caused by the lip between the finished and unfinished portions of the airfoil and was only seen at $\alpha \geq 3.4^\circ$.

4.8 Comparisons with Previous Work

In a previous study, Carnegie (1992) experimentally examined the boundary layer over two-dimensional forward- and backward-facing steps. Step heights of 1.59, 6.35, and

12.7 mm were examined. Chamfer angles of 0° and 45° were tested. The experimentally measured effects of the forward and backward facing steps on the boundary layer momentum thickness and shape factor were incorporated into the boundary layer analysis portion of an existing inviscid/viscous interaction airfoil analysis computer code. Carnegie used the modified computer code to analyse a CF-18 airfoil with leading edges of the patches at $x/c=0.03$ and 0.50 where $c=2.775$ m (109.25"). This chord length corresponded to a spanwise station of 3.69 m (145.28") on the CF-18 wing. The chord length of the patches was 10% of the airfoil chord and Re was 3×10^7 ; these values correspond to the full-scale CF-18 wing at representative flight conditions. Above an AOA of 4° , the viscous, separated flow analysis of the computer package produced unrealistic results (e.g., negative C_l values); consequently, Carnegie did not give any results for AOA above 4° .

Comparisons between Carnegie's lift curves and lift curves from the present experimental study are shown in Figures 4.31 and 4.32. All of Carnegie's results presented here are for unchamfered patches. Figure 4.31 shows the lift curves of Carnegie's computations for 2D patches at $x/c=0.03$ and experimental lift curves of 2D patches at $x/c=0.06$. The full-size equivalent thicknesses of the present 2D patches (see Table 3.3) correspond fairly well to the heights of Carnegie's patches. As seen in Figure 4.31, the experimental C_l values were somewhat higher than the computed lift coefficients for $\alpha \leq 3^\circ$, and much higher for $\alpha \geq 3.5^\circ$. In addition, the decreases in C_l for the experimental patches were not as great as the decreases for the computed cases. The experimental lift curves did not exhibit the sharp loss in lift around 3° as per the computational lift curves. Much of the discrepancy between the experimental and computational lift decrements for $\alpha \leq 3^\circ$ may be due to the fact that the leading edge of the patches was in different positions for the two sets of curves. A given patch at $x/c=0.03$ is substantially closer to the suction peak than one at $x/c=0.06$ and could

Figure 4.31: Lift Curve Comparisons Between Carnegie (1992) ($x/c=0.03$) and the Present Work for 2D Patches ($x/c=0.06$)

Figure 4.32: Lift Curve Comparisons Between Carnegie (1992) and the Present Work for 2D Patches at $x/c=0.50$

Table 4.3: Comparison of Computational (Carnegie 1992) and Experimental Drag Ratios for Two-Dimensional Patches

α (degrees) COMP/EXP	x/c COMP/EXP	DRAG RATIO C_{dp}/C_{dc}					
		COMPUTATIONAL			EXPERIMENTAL		
		h/c VALUES ($\times 10^{-3}$)			h/c VALUES ($\times 10^{-3}$)		
		0.57	2.29	4.58	0.68	2.72	5.69
1.0/1.0	0.03/0.06	1.08	1.30	1.70	1.26	1.74	2.58
	0.50/0.50	1.06	1.30	1.70	1.12	1.30	1.85
2.0/2.3	0.03/0.06	1.10	1.40	1.80	1.03	1.34	1.96
	0.50/0.50	1.07	1.30	1.75	1.06	1.19	1.51
3.0/3.4	0.03/0.06	1.10	1.45	1.95	1.05	1.08	1.14
	0.50/0.50	1.07	1.30	1.75	1.07	1.12	1.29
3.9/4.1	0.03/0.06	1.13	1.50	2.00	0.87	0.82	0.77
	0.50/0.50	1.07	1.30	1.70	1.00	1.03	1.09

well have a substantially greater detrimental effect on the performance of the CF-18 airfoil with its very sharp suction peak.

Figure 4.32 compares experimental and computational lift curves for 2D patches located at $x/c=0.50$. The results are generally similar to those of Figure 4.31. For $\alpha \leq 3^\circ$, the experimental and predicted lift decrements due to patches are, however, in quite good agreement in Figure 4.32.

From the experimental and computational comparisons, one can conclude that the computational results provide somewhat conservative estimates of lift coefficient loss when patches are added to a CF-18 airfoil, and that the computational model predicts stall at too low an angle of attack, both with and without ABDR patches.

Turning now to drag, Table 4.3 lists drag ratios computed by Carnegie, and experimental drag ratios, for two-dimensional patches of different thicknesses. The drag ratios are the ratio of C_{dp}/C_{dc} where C_{dp} is the drag coefficient of the airfoil with a patch and C_{dc} is the drag coefficient of the clean airfoil. The computed and experimental values are of comparable magnitude for $\alpha \leq 2.3^\circ$. At $\alpha \geq 3^\circ$, the experimental values are much lower than the computational values. It should, however, be noted that the low experimental ratios at high AOA are probably unrepresentative of behaviour at

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full-scale Reynolds numbers (see the discussion in the next section). As discussed for lift decrements, much of the discrepancy between the computational and experimental drag ratios for patches near the leading edge may well be due to the different chordwise positions of the patches, $x/c=0.03$ and $x/c=0.06$ for the computational and experimental cases, respectively.

4.9 Application to Full-Scale Aircraft

As mentioned in Section 3.1.1 (page 8), the test apparatus was designed to ensure fully rough flow, in the aerodynamic sense, over the patches in order to produce meaningful results.

Figure 3.14 (page 33) shows that C_d values for the clean airfoil were the same at all tunnel speeds or Reynolds numbers used in the experiments. This repeatability of C_d over a range of Reynolds numbers was also noted for all patched airfoil configurations.

Although consistent results were produced over the available Re range, the experimental Re was much lower than full-scale values of Reynolds number. The implications of the difference in Reynolds numbers is visually apparent in the pressure distributions and flow visualizations for an AOA of 3.4° and above. At these relatively high angles of attack, a substantial separation bubble appeared on the model airfoil at the leading edge ($Re \approx 2.4 \times 10^6$). At full-scale Reynolds numbers ($Re \approx 3.0 \times 10^7$) the separation bubble would most likely be extremely short and the boundary layer would undergo virtually instantaneous transition at the suction peak located at $x/c \approx 0.001$. In the case of a short separation bubble on a full-scale airfoil, the leading edge of a patch at $x/c=0.06$ would see a high pressure on its front face rather than the low pressure seen in the experiments (see page 57 for this discussion). Therefore, the experimental drag reduction due to patches on the model airfoil at high α values is

unrealistic for full-scale Re . The centreline drag coefficients for a full-scale airfoil with patches at $x/c=0.06$ and $\alpha \geq 3.4^\circ$ will be much higher than the experimental values. Since there was no overall flow separation at the lower angles of attack, the results of the experiments at $\alpha=0^\circ$, 1° , and 2.3° are thought to be applicable to the full-scale airfoil. The computed drag ratios likely give a reasonable measure of drag increments at full-scale for the higher angles of attack.

5. Conclusions and Recommendations

An experimental investigation of the effects of battle-damage repair patches on a CF-18 airfoil's performance has been performed and the results have been presented and discussed. Round, square and two-dimensional patches were tested; all patches had square, un-chamfered edges. The conclusions and recommendations resulting from the investigation are stated below.

5.1 Conclusions

Results showed that thicker patches ($h/c=5.69 \times 10^{-3}$) decreased the lift coefficient in the order of 10% below the lift coefficient value of the clean model airfoil. Lift coefficients for thin patches ($h/c=0.68 \times 10^{-3}$) were similar to the clean airfoil lift coefficients.

For the most part, as the patch thickness was increased, the drag on the airfoil increased. For example, a 2D thin patch ($h/c=0.68 \times 10^{-3}$) at $x/c=0.06$, $\alpha=0^\circ$, resulted in a C_d value of 0.0075 while a 2D thick patch ($h/c=5.69 \times 10^{-3}$) at the same position resulted in a C_d value of 0.0112. However, at 3.4° and 4.1° AOA, patches of medium and thick thickness placed at $x/c=0.06$ cause decreases in drag (usually 7-10%), compared to the clean airfoil at the same AOA. These surprising results are attributed to substantial laminar-separation bubbles which occur at the experimental Reynolds numbers; they are not considered representative of behaviour to be expected at full-scale Reynolds numbers. Flow visualization showed that a large separation bubble and subsequent reattachment zone was present at the leading edge of the model CF-18 airfoil at $\alpha \geq 3.4^\circ$.

Patches close to the leading edge (i.e., in a region of high velocity) produced

higher drag increments than patches at other chordwise positions. Patches at $x/c=0.50$ lowered C_l more than equivalent patches located at $x/c=0.06$ and 0.25 , although some of the C_l results may be misleading due to low density of static taps around the patch position.

Wake measurements at various spanwise stations showed that: round medium-thickness patches increased the overall drag of the airfoil by roughly 50% more than square medium patches; drag increased more at an AOA of 2.3° than at an AOA of 1° ; the drag increase was smaller for patches at a chordwise position of $x/c=0.50$ than at $x/c=0.06$. Overall drag force increments, ΔC_D , can be expressed in terms of an effective patch width, that is the effective width over which the patch-centreline drag increment can be considered to prevail. The round medium patch at $x/c=0.06$, $\alpha=1^\circ$ had an effective patch width of about 1.50, while the square medium patch at the same location had an effective patch width of about 1.05. When the angle of attack was increased to 2.3° for patches at the same chordwise location, the effective patch widths for the round and square medium patches were 1.91 and 1.23, respectively. For a square medium patch at $x/c=0.50$, $\alpha=1^\circ$, the effective patch width was approximately 0.89.

Experimental results and previous computational results compared fairly well for low angles of attack ($\alpha \leq 3^\circ$). Experimental results for $\alpha > 3^\circ$ are misleading due to the presence of large laminar-separation bubbles on the model airfoil.

A. Program Listings

A.1 Trav.bas

```
DECLARE SUB Calib (AA(), ni%, volt', density', velocity', which$)
DECLARE SUB Volts (badd%, model AS MODELTYPE, chan%, range%, func%, \
    azmode%, result!, er%)
DECLARE SUB ViaRegisterTest (badd%, er%)
DECLARE SUB InitModel (badd%, model AS ANY, initcnt&(), azmode%)
DECLARE SUB SetupModel (badd%, model AS ANY, azmode%)
DECLARE SUB PressAnyKey (a$)
DECLARE SUB GetInt (prompt$, x%)
DECLARE SUB PrintError (er%)
DECLARE SUB MainMenu (badd%, model AS MODELTYPE, initcnt&(), azmode%)
DECLARE SUB ViaInitialize (badd%)
DECLARE SUB AtoD1 (badd%, model AS MODELTYPE, chan%, range%, func%, \
    azmode%, result!, er%)
DECLARE SUB DAC (badd%, model AS MODELTYPE, chan%, count%, er%)
DECLARE SUB DigitalOutput (badd%, model AS MODELTYPE, chan%, state%, er%)
DECLARE SUB Relay (badd%, model AS MODELTYPE, chan%, state%, er%)
DECLARE SUB ResetCounter (badd%, model AS MODELTYPE, chan%, initcnt&(), er%)
DECLARE SUB DOWN (stair%)
DECLARE SUB UP (stair%)
' LABLINE
' LEVEL 1 QUICKBASIC SOFTWARE
' VERSION 4.0
' SCIZMETRIC INSTRUMENTS
' START UP ROUTINES
' July 1989

DIM model AS MODELTYPE
DIM initcnt&(4)
refres(1) = 100      'QuickBasic does not allow arrays to be included
refres(2) = 10000    'in records. Thus the reference resistances and
refres(3) = 100000   'and gains have been set as constants
gains(0) = 1
gains(1) = 10
gains(2) = 100
gains(3) = 500

CALL SetupModel(badd%, model, azmode%)
CALL InitModel(badd%, model, initcnt&(), azmode%)
func% = 0
CALL Volts(badd%, model, chan%, range%, func%, azmode%, result, er%)

CLS
'*****
'atmosphere= initial room pressure
'blres      = B.L. transducer voltage reading; ptotat - pc2
'blsum      = sum of all B.L. transducer measurements
'blvel      = average of all B.L. samples, representing the flow velocity
'blvolt     = initial voltage of boundary layer pressure transducer
'chan       = channel to read voltage from in Sciometric equipment
'            channel 1 = B.L. press trans, channel 2 = reference press trans
'            channel 3 = ps-pc2
'diff       = difference between successive B.L. velocity measurements
'filename    = name of data storage file
'fineness   = measurement step multiplication factor, intended to increase
'            the distance between measurements toward the outer edge of B L
```


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A. Program Listings

A.1 Trav.bas

```
DECLARE SUB Calib (AA(), n1%, volt', density', velocity', which$)
DECLARE SUB Volts (badd%, model AS MODELTYPE, chan%, range%, func%, \
                  azmode%, result', er%)
DECLARE SUB ViaRegisterTest (badd%, er%)
DECLARE SUB InitModel (badd%, model AS ANY, initcnt&(), azmode%)
DECLARE SUB SetupModel (badd%, model AS ANY, azmode%)
DECLARE SUB PressAnyKey (a$)
DECLARE SUB GetInt (prompt$, x%)
DECLARE SUB PrintError (er%)
DECLARE SUB MainMenu (badd%, model AS MODELTYPE, initcnt&(), azmode%)
DECLARE SUB ViaInitialize (badd%)
DECLARE SUB AtoD1 (badd%, model AS MODELTYPE, chan%, range%, func%, \
                  azmode%, result!, er%)
DECLARE SUB DAC (badd%, model AS MODELTYPE, chan%, count%, er%)
DECLARE SUB DigitalOutput (badd%, model AS MODELTYPE, chan%, state%, er%)
DECLARE SUB Relay (badd%, model AS MODELTYPE, chan%, state%, er%)
DECLARE SUB ResetCounter (badd%, model AS MODELTYPE, chan%, initcnt&(), er%)
DECLARE SUB DOWN (stair%)
DECLARE SUB UP (stair%)
' LABLINE
' LEVEL 1 QUICKBASIC SOFTWARE
' VERSION 4.0
' SCIZMETRIC INSTRUMENTS
' START UP ROUTINES
' July 1989

DIM model AS MODELTYPE
DIM initcnt&(4)
refres(1) = 100      'QuickBasic does not allow arrays to be included
refres(2) = 10000    'in records Thus the reference resistances and
refres(3) = 100000   'and gains have been set as constants
gains(0) = 1
gains(1) = 10
gains(2) = 100
gains(3) = 500

CALL SetupModel(badd%, model, azmode%)
CALL InitModel(badd%, model, initcnt&(), azmode%)
func% = 0
CALL Volts(badd%, model, chan%, range%, func%, azmode%, result, er%)

CLS
'*****
'atmosphere= initial room pressure
'blres      = B.L. transducer voltage reading; ptotal - pc2
'blsum      = sum of all B.L. transducer measurements
'blvel      = average of all B.L. samples, representing the flow velocity
'blvolt     = initial voltage of boundary layer pressure transducer
'chan       = channel to read voltage from in Sciometric equipment
'            channel 1 = B.L. press trans, channel 2 = reference press trans
'            channel 3 = ps-pc2
'diff       = difference between successive B.L. velocity measurements
'filename    = name of data storage file
'fineness   = measurement step multiplication factor, intended to increase
'            the distance between measurements toward the outer edge of B L
```

```

'freest(2) = ptotal-pc2
'freedist = distance from last B L measurement to freestream measurement
'freeref(2) = corresponding reference vel at time of freestream measurement
freestat(2) = p-pc2
func% = units of channel ( 0 = DCVolt )
i = sample measurement counter
info = relevant information on wind tunnel run
initbl = BL pressure transducer voltage at zero velocity
initref = reference pressure transducer voltage at zero velocity
j = B L measurement/position counter
jmax = maximum value of variable 'j'
ok = response to yes or no question
pausetime = time allotted for movement of Pitot tube to new
            measurement position
position = distance from tunnel floor
refres = reference transducer voltage reading (pc1-pc2)
refsum = sum of all reference transducer measurements
refvel = average of all reference samples, representing the flow velocity
refvolt = initial voltage of reference pressure transducer
roomtemp = initial temperature of the room
samplenum = number of samples taken for each measurement
stair = number of times stepper motor must cycle to traverse distance
statres = pa-pc2 transducer voltage reading
stepdist = distance between measurement during B L traverse
sum = cumulative distance traversed over multi-samples
tolerance = difference in successive velocity measurements at edge of B L
travdist = total distance of B L traverse
U = non-dimensional velocity
vel = freestream velocity (used to set tunnel velocity)
velres = transducer voltage (used to set tunnel velocity)
wormratio = number of times stepper motor must cycle to traverse 1 mm.
            determine how far in real world 1 represents.
*****
      DIM blvel(100), refvel(100), position(100), U(100), AA(10), Aref(10)
      DIM statvel(100)

      R = 287.
      freedist = 10.
      stepdist = 4
      travdist = 100
      wormratio = 157.8
      samplenum% = 11
      fineness = 1
      tolerance = .001
      range% = 0
      on$ = "yes"
*****
      DETERMINE INITIAL PRESSURE TRANSDUCER VOLTAGES AT ZERO TUNNEL SPEED
*****
      INPUT "REMEMBER TO REPOSITION B L. STATIC PROBE!!!! ", crt$
10  PRINT "Measuring transducer voltages at 0 m/s"
      refinitsum = 0!
      blinitsum = 0!
      statinitsum = 0!
      FOR i% = 1 TO 10
        chan% = 1
        CALL Volts(badd%, model, chan%, range%, func%, azmode%, res1, er%)
        blinitsum = res1 + blinitsum
        chan% = 2
        CALL Volts(badd%, model, chan%, range%, func%, azmode%, res2, er%)
        refinitsum = res2 + refinitsum
        chan% = 3
        range% = 3
        CALL Volts(badd%, model, chan%, range%, func%, azmode%, res3, er%)
        range% = 0
        statinitsum = res3 + statinitsum
        PRINT res1, res2, res3
      NEXT i%

```

```

initbl = blinitsum / (10 * 1')
initref = refinitsum / (10 * 1')
initstat = statinitsum / (10 * 1')
400 INPUT "Is this a transducer calibration run? (y/n) ", on$
IF on$ = "y" THEN
4 INPUT "Enter calibration data output file number ", calfiles$
PRINT "Output data file name = TEST", calfiles$
INPUT "Is this satisfactory (y or n) ? ", ok$
IF ok$ = "n" THEN
GOTO 4
END IF
OPEN "c:\trav\calib\test" + calfiles$ + ".cal" FOR OUTPUT AS #1
5 INPUT "Set tunnel speed and hit return", crt
blres = 0'
refres = 0'
statres = 0'
FOR i% = 1 TO samplenum%
chan% = 1
CALL Volts(badd%, model, chan%, range%, func%, azmode%, res1, er%)
blres = res1 + blres
chan% = 2
CALL Volts(badd%, model, chan%, range%, func%, azmode%, res2, er%)
refres = res2 + refres
chan% = 3
range% = 3
CALL Volts(badd%, model, chan%, range%, func%, azmode%, res3, er%)
range% = 0
statres = res3 + statres
PRINT res1, res2, res3
NEXT i%
ref = (refres / (samplenum% * 1')) - initref
bl = (blres / (samplenum% * 1')) - initbl
stat = (statres / (samplenum% * 1')) - initstat
PRINT " ****"
INPUT "Enter B.L. (Pt-Pc2) manometer height (mm): ", BLhgt
PRINT " *****"
INPUT "Enter REFERENCE (Pc1-Pc2) manometer height (mm): ", REFhgt
PRINT " *****"
INPUT "Enter Ps-Pc2 manometer height (in): ", STAThgt
' convert from inches to mm
STAThgt = STAThgt * 25.4
PRINT "B.L. voltage = "; bl
PRINT "Reference voltage = "; ref
PRINT "Stat voltage = "; stat
PRINT "B.L. Manometer height = "; BLhgt
PRINT "REF Manometer height = "; REFhgt
PRINT "Stat. Manometer height = "; STAThgt
PRINT "More measurements (y/n/a)? "
INPUT "(a = abort last data set) ", query$
SELECT CASE query$
CASE "n"
WRITE #1, BLhgt, bl, REFhgt, ref, STAThgt, stat
CLOSE #1
GOTO 99
CASE "a"
PRINT "Last data set scrapped"
GOTO 5
CASE ELSE
WRITE #1, BLhgt, bl, REFhgt, ref, STAThgt, stat
GOTO 5
END SELECT
END IF
99 PRINT "Enter the date, airfoil angle, patch position, tunnel speed"
INPUT "of this run: ", info$
INPUT "Enter output file number: ", filenames$
INPUT "Enter room pressure (mm Hg): ", atmosphere
INPUT "Enter temperature of the room (Celsius): ", roomtemp
density = (atmosphere * 133.3224) / (R * (roomtemp + 273.15))

```

```

IF density = 0 THEN
    density = 1.2
END IF
***** 133 3224 is the conversion factor from mm Hg to Pascals*****

PRINT "Note = ", info$
PRINT "Output file name" = TEST", filename$
PRINT "Traverse distance" = ", travdist, " mm "
PRINT "Initial distance between measurements" = ", stepdist, " mm "
PRINT "Number of samples" = ", samplenum%
PRINT " "
PRINT "Air temperature" = ", roomtemp, " Celsius"
PRINT "Atmospheric pressure" = ", atmosphere, " mm Hg"
PRINT "Air density" = ", density, " Kg/c.metre"
PRINT "Initial B.L. press trans voltage" = ", initbl, " volts"
PRINT "Initial reference press trans voltage" = ", initref, " volts"
PRINT "Initial stat press trans voltage" = ", initstat, " volts"
PRINT " "
INPUT "Are these values satisfactory (y or n) ? ", ok$
IF ok$ = "n" THEN
    GOTO 10
END IF
PRINT " "
INPUT "SET TUNNEL VELOCITY AND HIT RETURN", crt$
PRINT
*****
PROMPT USER TO SET TUNNEL WIND VELOCITY THEN RECALL
PRESSURE TRANSDUCER CURVE FIT COEFFICIENTS
*****
m% = 1
OPEN "c:\trav\data\refpoly.dat" FOR INPUT AS #1
DO UNTIL EOF(1)
    INPUT #1, Aref(m%)
    m% = m% + 1
LOOP
nref% = m% - 1
CLOSE #1
***** AND BL PRESSURE TRANSDUCER CURVE FIT COEFFICIENTS ***
m% = 1
OPEN "c:\trav\data\blpoly.dat" FOR INPUT AS #2
DO UNTIL EOF(2)
    INPUT #2, Abl(m%)
    m% = m% + 1
LOOP
nbl% = m% - 1
CLOSE #2
***** AND STAT (Ps - Pc2) PRESS TRANS CURVE FIT COEFFICIENTS ***
m% = 1
OPEN "c:\trav\data\statpoly.dat" FOR INPUT AS #3
DO UNTIL EOF(3)
    INPUT #3, Astat(m%)
    m% = m% + 1
LOOP
nstat% = m% - 1
CLOSE #3
*****
chan% = 2
20 velsum = 0!
vel = 0
templ = 0
temp2 = 0
FOR i% = 1 TO samplenum%
    CALL Volts(badd%, model, chan%, range%, func%, azmode%, velres, er%)
    velsum = velsum + velres
    PRINT velres
NEXT i%
*****
5th ORDER POLYNOMIAL CURVE FIT TO REFERENCE TRANSDUCER

```

```

      CALIBRATION CURVE
*****
      voltvel = (velsum / (samplenum% * 1')) - initref
      switch$ = "ref"
      CALL Calib(Aref(), nref%, voltvel, density, vel, switch$)
      switch$ = "0"
      PRINT "The freestream velocity is ", vel, " m/s"
      INPUT "Is this satisfactory (y or n) ? ", ok$
      IF ok$ = "y" THEN
        GOTO 21
      ELSE
        GOTO 20
      END IF
121  blsum = 0
      refsum = 0
      statsum = 0
      PRINT "Taking freestream measurements at", sum, " mm "
      FOR i% = 1 TO samplenum%
        chan% = 1
        CALL Volts(badd%, model, chan%, range%, func%, azmode%, blres, er%)
        blsum = blsum + blres
        chan% = 2
        CALL Volts(badd%, model, chan%, range%, func%, azmode%, refres, er%)
        refsum = refsum + refres
        chan% = 3
        range% = 3
        CALL Volts(badd%, model, chan%, range%, func%, azmode%, statres, er%)
        range% = 0
        statsum = statsum + statres
        PRINT blres, refres, statres
      NEXT i%
      freebl = (blsum / (samplenum% * 1')) - initbl
      freeref = (refsum / (samplenum% * 1')) - initref
      freestat = (statsum / (samplenum% * 1')) - initstat
      PRINT "The freestream B.L. voltage is "; freebl
      PRINT "The freestream ref voltage is "; freeref
      PRINT "The freestream stat voltage is "; freestat
*****
      ' DUE TO THE UNAVOIDABLE FLEXURE OF THE PITOT TUBE, IT IS
      ' NECESSARY TO ALIGN THE TUBE TO THE TUNNEL FLOOR WHILE THE
      ' TUNNEL IS RUNNING
*****
21  PRINT "INITIALIZE PITOT TUBE HEIGHT "
25  INPUT "Enter direction of traverse (u,d or q) ", direct$
      IF direct$ = "q" THEN
        GOTO 22
      END IF
      INPUT "Enter traverse distance (mm) ", dist
      stair% = CINT(dist * wormratio)
      IF direct$ = "u" THEN
        CALL UP(stair%)
        GOTO 25
      END IF
      IF direct$ = "d" THEN
        CALL DOWN(stair%)
        GOTO 25
      END IF
*****
      ' WHILE THE B.L PITOT TUBE IS WITHIN PRESET MARGIN, STEP
      ' MEASURE VELOCITY/VOLTAGE, STEP AND MEASURE. AT EACH
      ' MEASURE POINT, TAKE THE AVERAGE OF MANY SAMPLES.
*****
22  sum = 0
23  INPUT "Enter direction of travel during measurements (u/d)", direct$
      IF direct$ = "u" OR direct$ = "d" THEN
        GOTO 24
      ELSE
        GOTO 23
      END IF

```

```

      END IF
24   j% = 0
      WHILE sum <= travdist
        IF sum = 0 THEN
          GOTO 26
        ELSE
          PRINT "stepping bl Pitot tube"
          stair% = CINT(stepdist * wormratio)
          IF direct$ = "u" THEN
            CALL UP(stair%)
          ELSE
            CALL DOWN(stair%)
          END IF
        END IF
        j% = j% + 1
        position(j%) = sum
        PRINT "Reading reference pressure and BL pressure at ", sum; " mm."
        sum = sum + stepdist
        stepdist = stepdist * fineness
        blsum = 0
        refsum = 0
        statsum = 0
        FOR i% = 1 TO samplenum%
          chan% = 1
          CALL Volts(badd%, model, chan%, range%, func%, azmode%, blres, er%)
          blsum = blsum + blres
          chan% = 2
          CALL Volts(badd%, model, chan%, range%, func%, azmode%, refres, er%)
          refsum = refsum + refres
          chan% = 3
          range% = 3
          CALL Volts(badd%, model, chan%, range%, func%, azmode%, statres, er%)
          range% = 0
          statsum = statsum + statres
          PRINT refres
        NEXT i%
        blvel(j%) = (blsum / (samplenum% + 1)) - initbl
        refvel(j%) = (refsum / (samplenum% + 1)) - initref
        statvel(j%) = (statsum / (samplenum% + 1)) - initstat
        PRINT "The bl voltage is      ", blvel(j%)
        PRINT "The reference voltage is ", refvel(j%)
        PRINT "The stat voltage is      "; statvel(j%)
        voltvel = blvel(j%)
        CALL Calib(Abl(), nbl%, voltvel, density, velbl, switch$)
        PRINT "The bl vel. is      "; velbl
        switch$ = "ref"
        voltvel = refvel(j%)
        CALL Calib(Aref(), nref%, voltvel, density, velref, switch$)
        switch$ = ""
        PRINT "The ref. vel. is      "; velref
        jmax% = j%
        IF sum = 0 THEN
          CALL PressAnyKey(a$)
        END IF
      WEND
      *****
      NOW MOVE OUT OF THE B.L. AND MEASURE THE FREESTREAM VELOCITY
      *****
30  PRINT
      stair% = CINT((freedist + travdist - position(jmax%)) * wormratio)
      stair% = CINT(wormratio * freedist)
      IF direct$ = "u" THEN
        CALL UP(stair%)
      ELSE
        CALL DOWN(stair%)
      END IF
      blsum = 0
      refsum = 0

```

```

statsum = 0
sum = sum - stepdist + freedist
PRINT "Taking freestream measurements at", sum, " mm "
FOR i% = 1 TO samplenum%
  chan% = 1
  CALL Volts(badd%, model, chan%, range%, func%, azmode%, blres, sr%)
  blsum = blsum + blres
  chan% = 2
  CALL Volts(badd%, model, chan%, range%, func%, azmode%, refres, sr%)
  refsum = refsum + refres
  chan% = 3
  range% = 3
  CALL Volts(badd%, model, chan%, range%, func%, azmode%, statres, sr%)
  range% = 0
  statsum = statsum + statres
  PRINT blres, refres, statres
NEXT i%
freebl2 = (blsum / (samplenum% + 1)) - initbl
freeref2 = (refsum / (samplenum% + 1)) - initref
freestat2 = (statsum / (samplenum% + 1)) - initstat
  PRINT "The freestream voltage is "; freebl2
  PRINT "The freestream ref voltage is "; freeref2
  PRINT "The freestream stat voltage is "; freestat2
'*****
'  STORE DATA INTO AN OUTPUT FILE FOR LATER ANALYSIS
'*****
  OPEN "c:\trav\data\test" + filename$ + ".dat" FOR OUTPUT AS #1
  WRITE #1, info$
  WRITE #1, atmosphere, roomtemp, density
  WRITE #1, initbl, initref
  WRITE #1, blvel(1), refvel(1), statvel(1), freebl2, freeref2, freestat2
  PRINT info$
  PRINT atmosphere, roomtemp, density
  PRINT initbl, initref
  PRINT freebl, freeref, freestat
  FOR j% = 1 TO jmax%
    WRITE #1, blvel(j%), refvel(j%), statvel(j%), position(j%)
    PRINT blvel(j%); refvel(j%); statvel(j%); position(j%)
  NEXT j%
  CLOSE #1
' **** inquire about another calibration run **** '
  INPUT "Another calibration run (y/n)", crun$
  IF crun$ = "y" THEN
    GOTO 400
  END IF
999

SUB Calib (AA(), ni%, volt, density, velocity, which$)
'*****
'  AN LEAST SQUARES POLYNOMIAL CURVE FIT OF THE 0.1 psi B L.
'  PRESSURE TRANSDUCER CALIBRATION CURVE IS UTILIZED TO
'  CONVERT THE TRANSDUCER VOLTAGE TO VELOCITY.
'*****
  FOR k% = 1 TO ni%
    press = press + AA(k%) * volt ^ (k% - 1)
  NEXT k%
  IF which$ = "ref" THEN
    velocity = SQR(ABS((2! * press) / density / 87))
  ELSE
    velocity = SQR(ABS((2! * press) / density))
  END IF
END SUB

[standard Labmate Subroutines have been deleted]

```


A.2 Calib.bas

```

DECLARE SUB Curve (A'(), n%, jmax%, voltage'(), pressure'())
DECLARE SUB GaussJ (n%, C'(), R'(), A'())
DECLARE SUB LeastSq (jmax%, x'(), fx'(), n%, C'(), R'())
DECLARE SUB Curve2 (A'(), n%, jmax%, voltage'(), pressure'())

DIM BLvlt(50), BLhgt Aref(10) Abl(10), C(10, 10), R(10)
DIM voltage(50), pressure(50), REFvlt(50), REFhgt
DIM REFpress(50), BLpress(50), press(50)
DIM oldvlt1(50), oldvlt2(50), oldpres1(50), oldpres2(50)
DIM STATvlt(50), STAThgt, Astat(10), STATpress(50), oldvlt3(50)
DIM oldpres3(50)
CLS
INPUT "Enter calibration file number ", filename$
44 PRINT "Enter calibration choice: "
PRINT "=> B L transducer (1)"
PRINT "=> Ref transducer (2) "
PRINT "=> Both transducers (ENTER)"
INPUT "          <-----> ", choice%

OPEN "test" + filename$ + ".cal" FOR INPUT AS #1
j% = 1
DO UNTIL EOF(1)
    INPUT #1, BLhgt, BLvlt(j%), REFhgt, REFvlt(j%), STAThgt, STATvlt(j%)
    PRINT BLhgt, BLvlt(j%), REFhgt, REFvlt(j%), STAThgt, STATvlt(j%)
    BLpress(j%) = 9.81 * BLhgt
    REFpress(j%) = 9.81 * REFhgt
    STATpress(j%) = 9.81 * STAThgt
    j% = j% + 1
LOOP
jmax% = j% - 1
CLOSE #1
OPEN "curvfit.dat" FOR INPUT AS #1
OPEN "curv2fit.dat" FOR INPUT AS #2
OPEN "curv3fit.dat" FOR INPUT AS #3
j% = 1
DO UNTIL EOF(1)
    INPUT #1, oldvlt1(j%), oldpres1(j%)
    j% = j% + 1
LOOP
oldjmax1% = j% - 1
j% = 1
DO UNTIL EOF(2)
    INPUT #2, oldvlt2(j%), oldpres2(j%)
    j% = j% + 1
LOOP
oldjmax2% = j% - 1
j% = 1
DO UNTIL EOF(3)
    INPUT #3, oldvlt3(j%), oldpres3(j%)
    j% = j% + 1
LOOP
oldjmax3% = j% - 1
CLOSE #1, #2, #3

SELECT CASE choice%
CASE 1
    INPUT "Enter the B.L. polynomial order required: ", BLn%
    PRINT "==== CALCULATING B.L. COEFFICIENTS ====="
    CALL LeastSq(jmax%, BLvlt(), BLpress(), BLn%, C(), R())
    CALL GaussJ(BLn%, C(), R(), Abl())

    INPUT "Enter (Y) to save the coefficients. ", ans$
    IF ans$ = "y" THEN
        OPEN "c:\trav\data\blpoly.dat" FOR OUTPUT AS #1
        FOR k% = 1 TO BLn%

```

```

        PRINT #1, Abl(k%)
    NEXT k%
    CLOSE #1
    PRINT "B.L. coefficients saved in file BLPOLY.DAT"
ELSE
    PRINT "B L Coefficients are not saved "
END IF
CALL Curve(Abl(), BLn%, jmax%, voltage(), pressure())

OPEN "calcurv1.dat" FOR OUTPUT AS #1
OPEN "curv1fit.dat" FOR OUTPUT AS #2
FOR j% = 1 TO jmax%
    PRINT #1, BLvolt(j%), BLpress(j%)
NEXT j%
FOR j% = 1 TO jmax%
    PRINT #2, voltage(j%), pressure(j%)
NEXT j%
CLOSE #1, #2

PRINT "Enter (Y) if you want a comparison with the "
INPUT "old calibration curve.    => ", ans$
IF ans$ = "y" THEN
    OPEN "old1.dat" FOR OUTPUT AS #1
    FOR j% = 1 TO oldjmax1%
        PRINT #1, oldvolt1(j%), oldpres1(j%)
    NEXT j%
    CLOSE #1
ELSE
    OPEN "old1.dat" FOR OUTPUT AS #1
    PRINT #1, nothing
    CLOSE #1
END IF

CASE 2
INPUT "Enter the REF polynomial order required: ", REFn%
PRINT "**** CALCULATING REFERENCE COEFFICIENTS ****"

CALL LeastSq(jmax%, REFvolt(), REFpress(), REFn%, C(), R())
CALL GaussJ(REFn%, C(), R(), Aref())
INPUT "Enter (Y) to save the coefficients. ", ans$
IF ans$ = "y" THEN
    OPEN "c:\trav\data\refpoly.dat" FOR OUTPUT AS #1
    FOR k% = 1 TO REFn%
        PRINT #1, Aref(k%)
    NEXT k%
    CLOSE #1
    PRINT "Ref coefficients saved in file REFPOLY.DAT"
ELSE
    PRINT "REFERENCE Coefficients are not saved."
END IF
CALL Curve(Aref(), REFn%, jmax%, voltage(), pressure())

OPEN "calcurv2.dat" FOR OUTPUT AS #1
OPEN "curv2fit.dat" FOR OUTPUT AS #2
FOR j% = 1 TO jmax%
    PRINT #1, REFvolt(j%), REFpress(j%)
NEXT j%
FOR j% = 1 TO jmax%
    PRINT #2, voltage(j%), pressure(j%)
NEXT j%
CLOSE #1, #2
PRINT "Enter (Y) if you want a comparison with the "
INPUT "old calibration curve.    => ", ans$
IF ans$ = "y" THEN
    OPEN "old2.dat" FOR OUTPUT AS #2
    FOR j% = 1 TO oldjmax2%
        PRINT #2, oldvolt1(j%), oldpres1(j%)
    NEXT j%

```

```

        CLOSE #2
    ELSE
        OPEN "old2.dat" FOR OUTPUT AS #2
        PRINT #2, nothing
        CLOSE #2
    END IF

CASE 0
    INPUT "Enter the B.L. polynomial order required: ", BLn%
    INPUT "Enter the REF polynomial order required: ", REFn%
    INPUT "Enter the STAT polynomial order required: ", STATn%
    PRINT "**** CALCULATING B.L. COEFFICIENTS ****"

    CALL LeastSq(jmax%, BLvolt(), BLpress(), BLn%, C(), R())
    CALL GaussJ(BLn%, C(), R(), Abl())

    PRINT "**** CALCULATING REFERENCE COEFFICIENTS ****"
    CALL LeastSq(jmax%, REFvolt(), REFpress(), REFn%, C(), R())
    CALL GaussJ(REFn%, C(), R(), Aref())

    PRINT "**** CALCULATING STAT COEFFICIENTS ****"
    CALL LeastSq(jmax%, STATvolt(), STATpress(), STATn%, C(), R())
    CALL GaussJ(STATn%, C(), R(), Astat())

    INPUT "Enter (Y) to save the coefficients. ", ans$
    IF ans$ = "y" THEN
        OPEN "c:\trav\data\blpoly.dat" FOR OUTPUT AS #1
        OPEN "c:\trav\data\refpoly.dat" FOR OUTPUT AS #2
        OPEN "c:\trav\data\statpoly.dat" FOR OUTPUT AS #3

        FOR k% = 1 TO BLn%
            PRINT #1, Abl(k%)
        NEXT k%

        FOR k% = 1 TO REFn%
            PRINT #2, Aref(k%)
        NEXT k%

        FOR k% = 1 TO STATn%
            PRINT #3, Astat(k%)
        NEXT k%
        CLOSE #1, #2, #3

        PRINT "B.L. coefficients saved in file BLPOLY.DAT"
        PRINT "Ref coefficients saved in file REFPOLY.DAT"
        PRINT "Stat coeff. saved in file STATPOLY.DAT"
    ELSE
        PRINT "B.L. and REF Coefficients are not saved."
    END IF

    CALL Curve(Abl(), BLn%, jmax%, voltage(), pressure())
    OPEN "calcurv1.dat" FOR OUTPUT AS #1
    OPEN "curvfit.dat" FOR OUTPUT AS #2
    FOR j% = 1 TO jmax%
        PRINT #1, BLvolt(j%), BLpress(j%)
    NEXT j%
    FOR j% = 1 TO jmax%
        PRINT #2, voltage(j%), pressure(j%)
        pressure(j%) = 0!
    NEXT j%
    CLOSE #1, #2

    CALL Curve(Aref(), REFn%, jmax%, voltage(), pressure())
    OPEN "calcurv2.dat" FOR OUTPUT AS #1
    OPEN "curv2fit.dat" FOR OUTPUT AS #2
    FOR j% = 1 TO jmax%
        PRINT #1, REFvolt(j%), REFpress(j%)
    NEXT j%

```

```

FOR j% = 1 TO jmax%
  PRINT #2, voltage(j%), pressure(j%)
NEXT j%
CLOSE #1, #2

CALL Curve2(Astat(), STATn%, jmax%, voltage(), pressure())
OPEN "calcurv3.dat" FOR OUTPUT AS #1
OPEN "curv3fit.dat" FOR OUTPUT AS #2
FOR j% = 1 TO jmax%
  PRINT #1, STATvolt(j%), STATpress(j%)
NEXT j%
FOR j% = 1 TO jmax%
  PRINT #2, voltage(j%), pressure(j%)
NEXT j%
CLOSE #1, #2

PRINT "Enter (Y) if you want a comparison with the "
INPUT "old calibration curves      => ", ans$
IF ans$ = "y" THEN
  OPEN "old1.dat" FOR OUTPUT AS #1
  OPEN "old2.dat" FOR OUTPUT AS #2
  OPEN "old3.dat" FOR OUTPUT AS #3
  FOR j% = 1 TO oldjmax1%
    PRINT #1, oldvolt1(j%), oldpres1(j%)
  NEXT j%
  FOR j% = 1 TO oldjmax2%
    PRINT #2, oldvolt2(j%), oldpres2(j%)
  NEXT j%
  FOR j% = 1 TO oldjmax3%
    PRINT #3, oldvolt3(j%), oldpres3(j%)
  NEXT j%
  CLOSE #1, #2, #3
ELSE
  OPEN "old1.dat" FOR OUTPUT AS #1
  OPEN "old2.dat" FOR OUTPUT AS #2
  OPEN "old3.dat" FOR OUTPUT AS #3
  PRINT #1, nothing
  PRINT #2, nothing
  PRINT #3, nothing
  CLOSE #1, #2, #3
END IF

CASE ELSE
  GOTO 44
END SELECT

SUB Curve (A(), n%, jmax%, voltage(), pressure())
  FOR j% = 1 TO jmax%
    voltage(j%) = j% * 4.3 / (jmax% + 1)
    FOR k% = 1 TO n%
      pressure(j%) = pressure(j%) + A(k%) * voltage(j%) ^ (k% - 1)
    NEXT k%
  NEXT j%
END SUB

SUB Curve2 (A(), n%, jmax%, voltage(), pressure())
  pressure(1) = 0
  FOR j% = 1 TO jmax%
    voltage(j%) = j% * .007 / (jmax% + 1)
    FOR k% = 1 TO n%
      pressure(j%) = pressure(j%) + A(k%) * voltage(j%) ^ (k% - 1)
    NEXT k%
  NEXT j%
END SUB

SUB GaussJ (n%, C(), R(), A())
  k% = 1

```

```

30   temp = 1' / C(k%, k%)
      start% = k%
      FOR j% = start% TO n%
        C(k%, j%) = C(k%, j%) * temp
      NEXT j%
      R(k%) = R(k%) * temp
      j% = 1
20   IF k% = j% THEN
      GOTO 10
    END IF
      temp = C(j%, k%)
      start% = k%
      FOR l% = start% TO n%
        C(j%, l%) = C(j%, l%) - C(k%, l%) * temp
      NEXT l%
      R(j%) = R(j%) - R(k%) * temp
10   IF j% < n% THEN
      j% = j% + 1
      GOTO 20
    END IF
      IF k% < n% THEN
        k% = k% + 1
        GOTO 30
      END IF
      FOR k% = 1 TO n%
        A(k%) = R(k%)
      NEXT k%
END SUB

SUB LeastSq (jmax%, x(), fx(), n%, C(), R())
  FOR k% = 1 TO n%
    FOR l% = 1 TO n%
      FOR j% = 1 TO jmax%
        C(k%, l%) = C(k%, l%) + x(j%) ^ (l% + k% - 2)
      NEXT j%
    NEXT l%
  NEXT k%
  FOR k% = 1 TO n%
    FOR j% = 1 TO jmax%
      R(k%) = R(k%) + (fx(j%) * x(j%) ^ (k% - 1))
    NEXT j%
  NEXT k%
END SUB

```

A.3 Drag.c

/* Drag Analyser KJB Sept. 1994 - March-April 1995
 ABDR thesis work
 to obtain the drag coeff. from the pressure wake measured in the wind tunnel

Using the Melville-Jones equation

$Cd = \int (Cd') d(y/c) \quad Cd' = 2 \sqrt{g-p} (1 - \sqrt{g})$
 $g = (H - P_o) / (H_o - P_o) \quad p = (P - P_o) / (H_o - P_o)$
 where H_o, P_o = total head & static pressure in undisturbed stream
 H, P = total head & static press. in wake

When the measured values differ less than the 0.0055 (eg. outside of the wake), the values are averaged and used as freestream values for the calculations.

Variables:

MAX - maximum number of measured points
 CHORD - chord of the airfoil (metres)
 maxline - maximum length of the comment line in the input file
 j - general counter
 ntot - total # of polynomial coefficients for the $P_{tot}-P_{c2}$ meas.
 nref - tot. # of poly. coeff. for the reference press. meas. ($P_{c1}-P_{c2}$)
 nstat - tot. # of poly. coeff. for the stat press. meas. ($P-P_{c2}$)
 info - descriptive text
 atm - atmospheric pressure (Pa)
 rmtemp - room temperature (C)
 dens - air density (kg/m^3)
 deltax - probe step distance (mm)
 inittot - initial total press. meas. from wake plane ($P_{tot}-P_{c2}$) (Volts)
 initref - initial reference press. meas. ($P_{c1}-P_{c2}$) (Volts)
 initstat - initial static press. meas. from wake plane ($P-P_{c2}$) (Volts)
 freetot - last total press. meas. from the wake plane (Volts)
 freeref - last reference press. meas. (Volts)
 freestat - last static press. meas. from the wake plane (Volts)
 totvolt - measured total press. voltage during traverse (Volts)
 refvolt - measured reference press. volt. during traverse (Volts)
 statvolt - meas. static press. volt. during traverse (Volts)
 Atot - polynomial coeff.s for the total press. calibration
 Aref - polynomial coeff.s for the reference press. calibration
 Astat - polynomial coeff.s for the static press. calibration
 $P_{tPc2}, P_{c1Pc2}, P_{Pc2}$ - ($P_{total}-P_{c2}$), ($P_{c1}-P_{c2}$), ($P_{c2}-P$), respectively
 $P_{tPc2fs}(2), P_{c1Pc2fs}(2), P_{Pc2fs}(2)$ - same as above for the freestream [Pa]
 H_oP_o, P_o, H_P_o - (H_o-P_o), ($P-P_o$), ($H-P_o$), respectively [Pa]
 ratio1, ratio2 - Pdyn ratio at beginning, end of wake
 Re - Reynolds number
 pts - number of data points
 position - wake traverse position
 Cd - Drag Coefficient
 Sratio - Static press. ratio ($P-P_{c2}$)/($P_{c1}-P_{c2}$)
 */

#include <stdio.h>
#include <math.h>

```

#define MAX 100
#define CHORD 0.5588      /* 22" in metres */
#define DIFF 0.0055

void calib(float [],int , float , float *);

main (int argc, char *argv[]) {
    int maxline,j,jmax,jend,jstart,n,ntot,nref,nstat,pts;
    char info[50];
    float atm,rmtemp,dens,inittot,initref,initstat,freetot,freeref,freestat;
    float freetot2,freeref2,freestat2;
    float totvolt,refvolt,statvolt;
    float Atot[5],Aref[5],Astat[5],PtPc2fs,Pc1Pc2fs,PPc2fs;
    float PtPc2fs2,Pc1Pc2fs2,PPc2fs2,deltay,ratio[MAX],Re;
    float PtPc2[MAX],Pc1Pc2[MAX],PPc2[MAX],HoPo,PPo,HPo,Cd,position[MAX];
    float PPc2start,PPc2end,ratio1,ratio2,sum,Sratio;
    FILE *fp, *fp2, *fp3, *fp4, *fp5, *fp6;

    if ((fp = fopen(argv[1],"r"))==NULL){
        printf("Can't open %s\n", argv[1]);
        return 1;
    }
    /* read info line */
    maxline=50;
    fgets(info,maxline,fp);
    printf("%s",info);
    /* read atmospheric press.,rm.temp., density */
    fscanf(fp,"%f,%f,%f", &atm, &rmtemp, &dens);
    /* read initial, b.l. & ref. press. */
    fscanf(fp,"%f,%f", &inittot,&initref);
    /* read initial freestream tot & ref. */
    fscanf(fp,"%f,%f,%f,%f,%f,%f",&freetot,&freeref,&freestat, \
    &freetot2,&freeref2,&freestat2);
    /* read in the press. transducer calibration polynomial curve
       fit coeff.s sent from calibration software */
    fp2 = fopen("blpoly.dat","r");
    ntot=1;
    while (fscanf(fp2,"%f",&Atot[ntot])!=EOF) {
        printf("%f ", Atot[ntot++]);
    }
    fclose(fp2);
    printf("%i\n",--ntot);
    fp3 = fopen("refpoly.dat","r");
    nref=1;
    while (fscanf(fp3,"%f",&Aref[nref]) != EOF ) {
        printf("%f ", Aref[nref++]);
    }
    printf("%i\n",--nref);
    fclose(fp3);
    fp4 = fopen("statpoly.dat","r");
    nstat=1;
    while (fscanf(fp4,"%f",&Astat[nstat]) != EOF ) {
        printf("%f ", Astat[nstat++]);
    }
}

```

```

printf("%i\n",--nstat);
fclose(fp4);
/* calculate press. for freestream voltages */
calib(Atot,ntot,freetot,&PtPc2fs);
calib(Aref,nref,freeref,&Pc1Pc2fs);
calib(Astat,nstat,freestat,&PPc2fs);

calib(Atot,ntot,freetot2,&PtPc2fs2);
calib(Aref,nref,freeref2,&Pc1Pc2fs2);
calib(Astat,nstat,freestat2,&PPc2fs2);
printf("%f %f %f %f\n", PtPc2fs,Pc1Pc2fs,PPc2fs,PtPc2fs/Pc1Pc2fs);
printf("P-Pc2/Pc1-Pc2 = %f\n", PPc2fs2/Pc1Pc2fs2);
printf(" Pdym/Pc1-Pc2 = %f\n", (PtPc2fs2+PPc2fs2)/Pc1Pc2fs2);
/* open output file for position,PtPc2/Pc1Pc2,PPc2/Pc1Pc2 */
fp5 = fopen("wake.plot","w");
j=1; Cd = 0;
do {
/* read voltage levels for tot,freestr,static & position */
fscanf(fp,"%f,%f,%f,%f",&totvolt,&refvolt,&statvolt,&position[j]);
/* printf("%f %.8f %f %f %i\n", totvolt, refvolt,statvolt, position[j],j); */
calib(Atot,ntot,totvolt,&PtPc2[j]);
calib(Aref,nref,refvolt,&Pc1Pc2[j]);
calib(Astat,nstat,statvolt,&PPc2[j]);
ratio[j]=(PtPc2[j]+PPc2[j])/Pc1Pc2[j];
Sratio+=PPc2[j]/Pc1Pc2[j];
printf("%.2f %f\n",position[j], ratio[j]);
fprintf(fp5,"%f %f %f %f\n",position[j],PtPc2[j]/Pc1Pc2[j], \
PPc2[j]/Pc1Pc2[j],(PtPc2[j]+PPc2[j])/Pc1Pc2[j]);

++j;
} while (getc(fp) != EOF);
jmax=j-1;n=0;sum=0;ratio1=0;ratio2=0;jend=0;
Sratio/=jmax;
printf("jmax:%i\n",jmax);
for (j=2;j <= jmax;j++) { /* determine 'freestream' values */
if ((fabs(ratio[j]-ratio[j-1])<DIFF)&& \
(fabs(ratio[j+1]-ratio[j])<DIFF)){
sum+=ratio[j-1];
if((ratio1>0) && (jend==0)&&(j>jstart+3)) {
/* determine the end of the wake */
jend=j; }
n++; }
else if (((fabs(ratio[j]-ratio[j-1])<DIFF) && \
(fabs(ratio[j+1]-ratio[j])>=DIFF))&& ((j+1)<jmax/2)) {
sum+=ratio[j];n++; ratio1=sum/n; sum=0; n=0;jstart=j; }
/* determine the start of the wake and ratio1 */
else if ((fabs(ratio[j]-ratio[j-1]) < DIFF) && \
(j==jmax)){
sum+=ratio[j];n++; ratio2=sum/n; }
else printf(" ");
}
printf("ratio1:%f %i ratio2:%f %i\n", ratio1,jstart,ratio2,jend);
printf(" Pdym/Pc1-Pc2 = %f\n", (ratio1+ratio2)/2.0);
for (j=1;j<=jstart;j++) {

```



```

    PPc2start+=PPc2[j];}
    PPc2start/=jstart;
    for (j=jend;j<=jmax;j++){
        PPc2end+=PPc2[j];}
    PPc2end/=(jmax-jend+1);
printf ("PPc2start: %f, PPc2end: %f \n",PPc2start,PPc2end);
printf("P-Pc2/Pc1-Pc2 = %f\n", Sratio);
deltay=position[4]-position[3]; /* arbitrary choice */
for (j=1;j<=jmax;j++) {
    if (j<=jstart) {
        HoPo = Pc1Pc2[j] * ratio1;
        PPo = -PPc2[j] + PPc2start;
        HPo = PtPc2[j] + PPc2start; }
    else if (j>=jend) {
        HoPo = Pc1Pc2[j] * ratio2;
        PPo = -PPc2[j] + PPc2end;
        HPo = PtPc2[j] + PPc2end; }
    else {
        HoPo = Pc1Pc2[j] * (ratio1+(ratio2-ratio1) \
            *(j-jstart)/(jend-jstart));
        PPo = -PPc2[j] + (PPc2start+(PPc2end-PPc2start) \
            *(j-jstart)/(jend-jstart));
        HPo = PtPc2[j] + (PPc2start+(PPc2end-PPc2start) \
            *(j-jstart)/(jend-jstart)); }
    Cd += sqrt(HPo/HoPo - PPo/HoPo)*(1-sqrt(HPo/HoPo)) \
        * (deltay)/CHORD/1000;
printf ("HoPo:%lf,PPo:%lf,HPo:%lf,dCd:%lf \n ",HoPo,PPo,HPo,\
    sqrt(HPo/HoPo - PPo/HoPo)*(1-sqrt(HPo/HoPo)) *(deltay)/CHORD/1000);
}
Cd *= 2;
printf (" %f ", Cd);
fclose(fp);
fclose(fp5);
/* in the following line, 1.136=air density, .0000166=air viscosity @ 100F */
Re=CHORD/0.0000166*sqrt(HoPo*2/1.136);
printf("Re: %lf ",Re);
/* open output file for recording of Cd value */
fp6 = fopen("Cd.values","a");
fprintf(fp6,"Info: %s Drag: %f Re: %f %s\n", info,Cd,Re,argv[1]);
fclose(fp6);
}

void calib(float AA[],int n1, float volt, float *press) {
    int k;
    k=0; *press=0;
    for(k=1;k<=n1;k++){
        *press = *press + AA[k]* pow(volt,(k-1));
    }
    if (*press < 0 )
        *press = *press * (-1);
}

```

A.4 Lift.c

```
/* Lift analyzer for ABDR thesis
   Kevin Black Feb.1995
```

```
usage: lift filename
```

```
Input format: On individual lines of a text file in this order:
```

```
alpha (degrees), atm.press., Pc1, Pc2, Ptap1, Ptap2, ..., Ptap33
Pressures are in Inches of Water.
```

```
The EOF of the input file must be on the same line as Ptap33. (ie.
the last line must not contain a Carriage Return)
```

```
The Tap Coordinates file is in the following format in a text file:
```

```
x1/c y1/c
```

```
x2/c y2/c
```

```
etc.
```

```
Start with the trailing edge tap on the top surface, work forward,
around to the bottom surface and end with the trailing edge tap
on the bottom surface. Similar EOF requirement as above.
```

```
The output text file "cpvalues" has the x/c values in the first
column and the associated Cp values in the second column.
```

```
The output text file "lift.drag" lists the calculated alpha, lift
and drag.
```

```
Variables:
```

```
i - general counter
```

```
xc, yc - normalized x and y coordinates of the static taps
```

```
patm - atmospheric pressure (in.H2O)
```

```
ptaps - in.H2O measurements from the static taps
```

```
pc1,pc2 - measured reference press. (in.H2O)
```

```
dref - pc1-pc2 (Pa)
```

```
dp - ptaps-pc2 (Pa)
```

```
degrees - angle of attack in degrees; input
```

```
alpha - angle of attack in radians
```

```
term1,term2,term3 - intermediate terms for the calc. of Cp
```

```
Cp - Pressure Coefficient
```

```
 $Cp = (P_{tap} - P_{c2}) / q - (P_{inf} - P_{c2}) / (P_{c1} - P_{c2}) * (P_{c1} - P_{c2}) / q$ 
```

```
q=freestream dynamic pressure
```

```
2nd and 3rd terms are from tunnel calibrations
```

```
2nd term = 0.13084*(x/l)+0.0929 [Pa] l=test section length
```

```
3rd term = -0.06376*(x/l)+0.9046 [Pa] x=dist from front of section
```

```
N,C - Normal and Chordwise Force Coeff.
```

```
Lift,Drag - Lift and Drag Coeff.
```

```
*/
```

```
#include <stdio.h>
```

```
#include <math.h>
```

```
main (int argc, char *argv[]) {
```

```
int i;
```

```
double xc[35],yc[35],patm,ptaps[35],dp,degrees,alpha;
```

```
double term1,term2,term3,Cp[34],N,C,Lift,Drag;
```

```
double pc1,pc2,dref,q;
```

```

FILE *fp, *fp2, *fp3;

/* SEE IF THE FILE EXISTS */
if ((fp = fopen(argv[1], "r")) == NULL) {
    printf("Can't open %s\n", argv[1]);
    return 1; }

/* READ IN STATIC TAP COORDINATES */
fp2 = fopen("/files1/home/kblack/thesis/tapcoords", "r");
i=1;
while (fscanf(fp2, "%lf %lf", &xc[i], &yc[i]) != EOF) {
    ++i; }
fclose(fp2);
xc[0]=1.000; xc[34]=1.000;
/* T.E. yc is the average of the real top and bott. yc's */
yc[0]=0.008605; yc[34]=0.008605;
/* READ IN ANGLE OF ATTACK; CONVERT TO RADIANS */
fscanf(fp, "%lf", &degrees);
printf("%lf \n", degrees);
alpha=degrees*3.1415293/180.0;
/* READ IN MANOMETER READINGS */
/* read Patm */
fscanf(fp, "%lf", &patm);
/* read Pc1 */
fscanf(fp, "%lf", &pc1);
/* read Pc2 */
fscanf(fp, "%lf", &pc2);
dref= -(pc1-pc2)*25.4*9.81;
/* read 33 Ptaps */
i=1;
do {
    fscanf(fp, "%lf", &ptaps[i]);
    ++i;
} while (getc(fp) != EOF);
printf("%i \n", i);
fclose(fp);

printf("Enter the P-Pc2/Pc1-Pc2 ratio: ");
scanf("%lf", &term2);
printf("Enter the Pdym/Pc1-Pc2 ratio: ");
scanf("%lf", &term3);
q=term3*dref;

/* DETERMINE Cp VALUES FROM MANOMETER READINGS */
for(i=1; i<=34; i++) {
    dp=-(ptaps[i]-pc2)*25.4*9.81;
    term1=dp/q;
    Cp[i]=term1+term2/term3; }
/* make trailing edge Cp avr. of closest 2 values */
Cp[0]=(Cp[1]+Cp[33])/2;
Cp[34]=Cp[0];

/* OUTPUT Cp VALUES TO AN OUTPUT FILE */
fp3=fopen("cpvalues", "w");

```

```

i=0;
for(i=0;i<=34;i++) {
    fprintf(fp3,"%lf %lf\n", xc[i],Cp[i]); }
fclose(fp3);

/* FIND THE NORMAL AND CHORDWISE COEFFICIENTS */
N=0.0; C=0.0; i=0;
for (i=0;i<=33;i++) {
    N=N+(Cp[i+1]+Cp[i])/2*(xc[i+1]-xc[i]);
    C=C-(Cp[i+1]+Cp[i])/2*(yc[i+1]-yc[i]); }
printf("%lf %lf",N,C);

/* COMPOSE LIFT AND DRAG COEFFICIENTS */
/* remember that C is actually a negative value */
Lift=N*cos(alpha)+C*sin(alpha);
Drag=N*sin(alpha)-C*cos(alpha);
printf("%lf %lf", Lift, Drag);
/* output lift and drag */
fp3=fopen("lift.drag","a");
fprintf(fp3,"%s\n Cl: %lf\n Cd: %lf\nAlpha: %lf degrees\n", \
argv[1],Lift,Drag,degrees);
fclose(fp3); }

```

B. Test Run Outputs

B.1 Sample of Wake Traverse

```
"5jul95 6deg clean 9.56 88%"
758,22,1.19302
-.0011,.007
1.865645,1.931818,4.203291E-03,1.893827,1.909273,3.113109E-03 freestream values
1.865645,1.931818,4.203291E-03,0 Po-Pc2, Pc1-Pc2, Pc2-Ps, probe position
1.831827,1.928364,4.222745E-03,6
1.791373,1.928273,4.223018E-03,10
1.751554,1.923636,4.276654E-03,15
1.692373,1.928273,4.305382E-03,20
1.6241,1.922909,4.319927E-03,25
1.555191,1.916909,4.36329E-03,30
1.4861,1.913,4.352382E-03,35
1.416827,1.913,4.354837E-03,40
1.329282,1.912,4.349837E-03,45
1.258373,1.908091,4.339745E-03,50
1.190009,1.907,4.345018E-03,55
1.118555,1.907364,4.297382E-03,60
1.059191,1.907727,4.236564E-03,65
.9982818,1.906,4.152291E-03,70
.9544637,1.910818,4.105382E-03,75
.9331,1.913545,4.066746E-03,80
.9256455,1.912546,4.053654E-03,85
1.202464,1.915273,3.848836E-03,90
1.564827,1.912545,.0036842,95
1.829918,1.911182,3.535836E-03,100
1.888282,1.908455,.0034592,105
1.892554,1.909091,3.346745E-03,110
1.892827,1.906182,3.324382E-03,115
1.8941,1.910636,.0033512,120
1.892918,1.908273,3.284563E-03,125
1.896282,1.91,3.241018E-03,130
1.895282,1.909,3.201655E-03,135
1.893918,1.907091,3.236473E-03,140
1.896191,1.909636,3.205927E-03,145
1.894736,1.911,3.171654E-03,150
1.893282,1.909909,3.131927E-03,155
1.896827,1.909818,3.114563E-03,160
```

B.2 Sample of Static Tap Readings

This sample of static tap readings corresponds to the wake measurement on the previous page

6.0	angle of attack
33.2	atmospheric pressure
22.1	Pc1
32.71	Pc2
34.3	tap #1
34.73	tap #2
35.21	tap #3
35.98	.
36.68	.
37.05	.
37.54	
38.	
40.2	
47.2	
50.07	
50.03	
49.78	
49.56	
49.48	
49.38	
49.5	
32.7	
22.3	
22.21	
22.73	
24.53	
26.42	
27.62	
28.76	
29.4	
30.5	
31.84	
32.39	.
32.8	.
33.07	.
33.27	tap #32
33.51	tap #33

Don't tell me I'm finished!?! You've got to be kidding!!

I highly recommend the use of $\LaTeX$. It kicks butt.

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END

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FIN