THE EFFECTS OF AN ARRANGEMENT OF VORTEX GENERATORS INSTALLED TO ELIMINATE WIND TUNNEL DIFFUSER SEPARATION

by

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SUMMARY

Diffuser flow separation in the UTIAS low speed wind tunnel has been largely eliminated by the installation of an array of vortex generators ahead of the original separation region.

The wind tunnel speed steadiness has been markedly improved without significant loss in maximum speed capability. The wind tunnel turbulence factor improved slightly.

This report includes a discussion of the design of the vortex generator installation and some before-and-after comparisons of wind tunnel performance data. The effects of the vortex generators on the diffuser boundary layer profiles are also shown.
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<th>Symbol</th>
<th>Description</th>
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<tr>
<td>$A_o$</td>
<td>cross section area of wind tunnel test section</td>
</tr>
<tr>
<td>$b$</td>
<td>vortex generator span</td>
</tr>
<tr>
<td>$c_r$</td>
<td>vortex generator root chord</td>
</tr>
<tr>
<td>$c_t$</td>
<td>vortex generator tip chord</td>
</tr>
<tr>
<td>$ER$</td>
<td>wind tunnel energy ratio</td>
</tr>
<tr>
<td>$p_A, p_B, p_C$</td>
<td>static pressure at stations A, B, and C. See stations diagram, Fig. 2</td>
</tr>
<tr>
<td>$\Delta p_1$</td>
<td>$p_B - p_A$</td>
</tr>
<tr>
<td>$\Delta p_2$</td>
<td>$p_C - p_A$</td>
</tr>
<tr>
<td>$\Delta p_D$</td>
<td>static pressure rise in diffuser</td>
</tr>
<tr>
<td>$q_o$</td>
<td>test section dynamic pressure</td>
</tr>
<tr>
<td>$s$</td>
<td>spacing between quarter-chord points of adjacent vortex generators</td>
</tr>
<tr>
<td>$V_o$</td>
<td>air speed through wind tunnel test section</td>
</tr>
<tr>
<td>$\delta$</td>
<td>boundary layer thickness, $u/U_o$ 0.99</td>
</tr>
<tr>
<td>$\delta'$</td>
<td>boundary layer thickness, $u/U_o$ 0.707</td>
</tr>
<tr>
<td>$\delta^*$</td>
<td>boundary layer displacement thickness</td>
</tr>
<tr>
<td>$\rho$</td>
<td>air density</td>
</tr>
<tr>
<td>$\sigma_v$</td>
<td>standard deviation of wind tunnel test section speed fluctuations (RMS value of fluctuating component)</td>
</tr>
</tbody>
</table>
I. INTRODUCTION

Figure 1 is a general arrangement drawing of the University of Toronto low speed wind tunnel. It had been suspected for some time that the flow through the fourth diffuser, the diffuser immediately downstream of the fan, was separating from the walls. Some previous researchers who had reason to be inside the diffuser while the wind tunnel was operating found that they could lie on the diffuser floor and the main stream of air would pass by overhead, leaving them in a deep region of dead air.

As an upper limit for an efficient diffuser, Pope (Ref. 9) suggests an equivalent circular cone divergence angle of about 8 degrees, but for this particular diffuser it is 13.1 degrees, the result of a compromise when the wind tunnel had to be designed to fit within an existing building.

The aim of the present project has been to improve the wind tunnel steadiness and performance by using the vortex generator mixing principle to reduce or eliminate the region of separated flow.

II. DESCRIPTION OF FOURTH DIFFUSER

The wind tunnel duct cross section at the fan-and-straightener discharge station, designated here as station zero, is circular, 78 inches in diameter, with a concentric centre-body housing the drive motor. As shown in Fig. 2, all other numbered stations are designated by their distance in inches downstream of station zero.

A transition to a regular octagon occurs between stations 0.0 and 72.0, and some diffusion is realized through the tapering of the centre-body. From station 72.0 to 282.0 (the exit) the diffuser is straight-sided, ending in an 8 ft. by 12 ft. rectangle with corner fillets. The particulars are listed below:

| Cross section area, sta 0.0 | 21.3 sq. ft. |
| Cross section area, sta 72.0 | 31.6 sq. ft. |
| Cross section area, sta 282.0 | 88.0 sq. ft. |
| Overall expansion ratio | 4.13:1 |
| Total length (including transition) | 23.5 ft. |
| Equivalent circular cone angle | 13.1° |

On the same figure three other stations, lettered A, B, and C are shown in the fan-and-straightener system. Reference to them appears in Sec. V.
III. WOOL TUFT PHOTOGRAPHS

Some preliminary impressions of the nature of the flow through the diffuser were obtained by making motion pictures of wool tufts attached to the surfaces of the diffuser. The camera was fixed at the centre of the exit station of the diffuser to look upstream toward the fan. Figure 3 is a mosaic of several frames of the film which together show all the surfaces in the upstream half of the diffuser. It can be seen that on the floor the flow is reversed to the left of the centre line. The flow at the top, right side, and over the centrebody is smooth and attached. The flow on the left wall is quite poor, and the motion pictures showed that separation spread intermittently up this wall from the floor. It is most probable that this intermittency accounted for the wind tunnel speed unsteadiness which is discussed in Sec. V.

The separation on the floor of the diffuser is reflected in the test section velocity profiles measured by Laundry in 1954 (Ref. 11). He found a fairly large velocity defect of approximately 2% near the top of the test section, the portion corresponding to the bottom of the fourth diffuser.

It was planned to make before and after comparisons of the test section velocity distribution, but traversing gear which is presently being prepared could not be made available in time to include such results in the present paper.

IV. THE VORTEX GENERATORS

4.1 Historical Note

The vortex generator mixing principle was conceived and developed in 1946 by the wind tunnel group of the United Aircraft Corporation during a program directed toward eliminating boundary layer separation in the first diffuser of their wind tunnel (Ref. 2). They subsequently studied several other applications of vortex generators and by 1950 issued a summary report (Ref. 5) giving their test results and some design data.

Further work has been done by the NASA on the applications of vortex generators to wide-angle diffusers (Refs. 4, 6 and 8) and to problems of boundary layer-shock wave interaction at transonic speeds (Ref. 10). Vortex generators have been used on some aircraft to improve the flow through curved inlet ducts and to delay flow separation on the flying surfaces. One particular aircraft uses an array of variable-incidence vortex generators on the upper, outboard wing surfaces. These are linked to the aileron control system, and by delaying separation they allow the ailerons to remain effective down to quite low speeds.
4.2 Purpose and Description

A possible method of boundary layer control to prevent separation is to intermix high-energy, free stream air with the retarded boundary layer, thus obtaining a re-energized layer which has the ability to flow further against a given adverse pressure gradient. Turbulizers in the form of coarse grids might be used for this purpose but their drag is high and the intermixing is poor and not easily controlled because the wake of a grid contains vortices whose axes are perpendicular to the flow direction. On the other hand, if vortices having axes parallel to the flow direction are produced, more efficient mixing can be realized. Such a vortex is released at the free end of a lifting airfoil as in Fig. 4.

Figure 5 shows in plan view an array of such airfoils. It will be noted in the figure that adjacent airfoils are generating vortices of opposite sign. This has been found to be the configuration giving the most vigorous mixing (Ref. 2). In some applications where vortex generators are used to delay separation on a highly swept wing where transverse flow in the boundary layer occurs, it may be advantageous to have all the airfoils with the same orientation. Their beneficial influence as flow fences may then offset the less efficient mixing (Ref. 7).

4.3 Design of Vortex Generators

4.3.1 Planform

Theoretical and experimental studies in the literature indicate that maximum mixing is realized when the airfoils release only a concentrated tip vortex. This occurs when the airfoil develops constant spanwise circulation. Since the airfoil lies within the boundary layer, constant spanwise circulation requires that the airfoil be tapered an amount determined by the boundary layer profile. This would, in fact, require an infinite root chord, but taper ratios of two-to-one are generally satisfactory with the tip chord being about 1.6 times the airfoil span.

4.3.2 Span

Greatest mixing is realized when the tip vortex is released at approximately the edge of the boundary layer. Since the vortex core actually lies inboard of the physical tip of the airfoil, a span, b, of 1.2δ is the recommended value where δ is the boundary layer thickness (u = 0.99U0). Such a boundary layer edge may be difficult to locate precisely, and in such cases a span of 8 times δ' can be used where δ' is the distance from the surface to the point where the dynamic pressure
is half of that in the free stream \((u = 0.707U_o)\). In addition, some of the NASA literature recommends a vortex generator span of about 6 times \(\delta^*\) where \(\delta^*\) is the boundary layer displacement thickness. For the particular case investigated here it was found that the three values so obtained yielded nearly the same span.

4.3.3 Spacing

Referring again to Fig. 5, it will be noted that if fairly high angles of attack are used there will be a significant difference between the spacings of the quarter-chord points and the spacings of adjacent vortex cores. It has been found (Ref. 3) that regular spacing of the airfoil quarter-chords is slightly superior to regular spacing of vortex cores. The optimum spacing, \(s\), is about 3 spans; \(s/b = 3\).

4.3.4 Location of Vortex Generators

In diffuser applications the airfoils should all be placed at the same axial station, upstream of the initial separation by a distance of 10 to 20 times the local boundary layer thickness, \(\delta\). A value of approximately 15 \(\delta\) has been used in the present case.

4.4 Determination of the Separation Point

From the photographs of the wool tufts it appeared that separation first occurred on the floor of the diffuser very near the entrance. Using the equipment described in the Appendix, boundary layer profiles were determined at five ten-inch intervals: stations 80, 90, 100, 110 and 120 where station 72 is the end of the transition section. Figure 6 presents these five profiles, showing that separation occurs at about station 95, less than two feet from the downstream end of the transition section. Note that reversed flow in the separated region is not indicated by the data points because the probes used were forward-facing pitot tubes. Similar profiles measured on the walls and the top surface of the diffuser showed no significant separation, at least as far downstream as station 120, although the data from the left wall was somewhat erratic in keeping with the observed intermittent tuft reversings noted in Sec. III. Flow through the diffuser is quite slow and beyond station 120 the dynamic pressure was too weak to give a well-defined velocity profile.
4.5 Determination of Vortex Generator Design

As noted above, the vortex generators should lie about 15Δ ahead of the separation point. Rough extrapolations from the boundary layer profiles above indicated that the boundary layer thickness near station 30 (well inside the transition duct) was such that station 30 would lie 15 Δ ahead of the separation region beginning at station 95. Additional profiles were then obtained at stations 20 and 40 (Fig. 7) and by interpolation it was found that station 27 satisfied the 15 Δ criterion and that the boundary layer thickness there was 4.5 inches.

Hence the vortex generator configuration was chosen as follows:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quarter-chord location</td>
<td>station 27</td>
</tr>
<tr>
<td>Local boundary layer thickness, Δ</td>
<td>4.5 in.</td>
</tr>
<tr>
<td>Distance to separation point</td>
<td>68 in. (15.1 Δ)</td>
</tr>
<tr>
<td>Airfoil span, b = 1.2 Δ</td>
<td>5.5 in.</td>
</tr>
<tr>
<td>Tip chord, c_t = 1.6b</td>
<td>8.8 in.</td>
</tr>
<tr>
<td>Root chord, c_r = 2c_t</td>
<td>17.6 in.</td>
</tr>
<tr>
<td>Ideal spacing, s = 3b</td>
<td>16.5 in.</td>
</tr>
<tr>
<td>Tunnel circumference at station 27</td>
<td>247 in.</td>
</tr>
<tr>
<td>Number of airfoils</td>
<td>14.9</td>
</tr>
<tr>
<td>(nearest even number is 14)</td>
<td></td>
</tr>
<tr>
<td>Actual spacing, then, 247/14</td>
<td>17.6 in.</td>
</tr>
<tr>
<td>Spacing ratio, s/b</td>
<td>3.2</td>
</tr>
</tbody>
</table>
Coincidentally, the flow straighteners just ahead of the vortex generator station consist of seven radial vanes, so that there are exactly two vortex generators for each vane. Figure 8, a flat development of this part of the wind tunnel wall, shows the placement of the vortex generators with respect to the straightener vanes. It can be seen that the tip vortices will tend to sweep the wakes of the vanes up and away from the surface. This was expected to be superior to the opposite arrangement which would sweep these wakes down into the boundary layer on the surface.

Although it is not shown on the figure, the configuration is actually skewed 2-1/2 degrees, this being the average helix angle of residual rotation from the fan in the region of the vortex generators as determined by W. K. Bell in 1957 (unpublished work).

The vortex generator angle of attack was set at 15 degrees, the value recommended in most of the literature. Since vortex generators are power-consuming devices, a compromise is involved in the choice of the angle of attack because strong vortices imply high induced drag on the vortex-generating airfoil. As will be seen in Sec. V, the maximum wind tunnel speed was reduced about 1% by this installation.

Figure 9 shows a vortex generator. Two of these, one left- and one right-hand, were carved from wood and were used as "masters" for the fabrication of fourteen sheet metal copies which were installed in the wind tunnel. Two of these metal copies are shown in Fig. 10. Figure 11 shows the vortex generators in place on the surfaces of the wind tunnel transition section.

V. WIND TUNNEL PERFORMANCE BEFORE AND AFTER INSTALLATION OF VORTEX GENERATORS

5.1 Wind Tunnel Speed Steadiness

It was known that for a given setting of the wind tunnel controls, the actual test section speed fluctuated about the mean speed. Figure 12 is a time history of the test section dynamic pressure showing a typical amplitude and time scale for the fluctuations before the installation of the vortex generators. It will be noted that the major components of the fluctuations have periods of ten to fifteen seconds, commensurate with the time scale of massive changes such as the intermittent flow separation and attachment in the diffuser.

To obtain a numerical indicator of the unsteadiness, a fairly direct method was adopted whereby traces like that of Fig. 12 were converted by hand into digital form. The dynamic pressure was read from the traces at one-second intervals for runs of 180 to 200 seconds. These
readings, in punched card form, were then reduced by the University's IBM 7094 digital computer to yield the mean speed, \( V_0 \), and the standard deviation, \( \sigma_v \) (the RMS value of the fluctuating component). This was done for several wind tunnel speed settings. It was then possible to determine the ratio:

\[
\frac{\text{standard deviation of speed}}{\text{mean speed}} = \frac{\sigma_v}{V_0}
\]

This has been used as the indicator of unsteadiness. Before the installation of the vortex generators this was found to range from about 0.5% at low speeds to 0.15% at high speeds. The vortex generators markedly improved the speed steadiness. Figure 13 shows two time histories of the test section dynamic pressure, recorded at the highest tunnel setting and plotted to the same scale. Part A was recorded a few days before the installation of the vortex generators, and part B immediately after they were installed. In part A the difference between the maximum and minimum is about 1.5% of the mean value (the zero is some 15 inches off the figure). In part B the maximum to minimum difference is 0.4% of the mean, and there are periods of some 30 seconds or more where the change is barely greater than the line-width of the recording pen. The improvement in speed steadiness was most pronounced at the high end of the wind tunnel speed range. Figure 14 is a similar comparison at a lower speed, about 90 ft./sec., showing that the improvement is not great. Figure 15 shows the variation of the steadiness parameter \( \sigma_v/V_0 \) with test section speed both before and after the vortex generators were installed. Both of the curves show the trend toward improved steadiness with increasing speed, and the improvement due to the vortex generators is most pronounced at speeds above 100 ft./sec. In the high speed range the value of \( \sigma_v/V_0 \) flattens out at about 0.06%, which is of the same order as the resolving capability of the equipment. For even if the pressure transducer and the amplifiers are assumed perfect, the recording pen line width, which is about 0.015 inch, is about 0.1% of the 15 inches full scale deflection. The pen movement is proportional to the dynamic pressure, i.e., to speed squared, so that 0.1% variation in dynamic pressure implies 0.05% variation in speed. This is very nearly the limiting value found for \( \sigma_v/V_0 \). One's ability to read consistently the centre of the plotted line to the nearest hundredth of an inch became a significant factor.

5.2 Wind Tunnel Energy Ratio and Speed Capability

Throughout the wind tunnel duct, losses of total pressure occur. These losses are balanced by the pressure rise through the fan section, and when the wind tunnel is running at a steady speed the fan pressure rise equals the total head loss in the rest of the tunnel. Denoting the test section dynamic pressure as \( q_0 \), the ratio
fan pressure rise \( \frac{q_o}{q_o} \)

is the wind tunnel loss coefficient. The reciprocal of the loss coefficient, usually denoted ER, is the energy ratio of the wind tunnel.

Static pressure was measured at three axial stations on the walls of the fan-and-straightener section. Since this is a constant-area section the axial velocity is constant and, provided that the rotational component is not large, the rise in total head appears as a static pressure rise only. With reference again to Fig. 2, station A was 5 inches ahead of the leading edge of the fan blades. Stations B and C were respectively 16 and 52 inches aft of the leading edge of the fan blades, station C being in line with the aft end of the set of seven straightener vanes. Three pressure taps spaced about the circumference at each station were used, the pressures from each set of three being averaged by connecting the pressure leads in common onto one manometer. Measurements were made of the pressure rises:

\[
\Delta p_1 = p_B - p_A
\]

\[
\Delta p_2 = p_C - p_A
\]

It was found that \( \Delta p_1 \) and \( \Delta p_2 \) were very nearly proportional to \( q_o \), and

\[
\frac{\Delta p_1}{q_o} = 0.228
\]

\[
\frac{\Delta p_2}{q_o} = 0.260
\]

It may be noted here that \( \Delta p_2 \) is greater than \( \Delta p_1 \), indicating that the straightener vanes have the desired effect of producing a pressure rise by directing the rotating flow from the fan into principally axial flow.

Treating the fan-and-straightener system as a unit, the wind tunnel loss coefficient is \( \Delta p_2/q_o = 0.260 \), and the energy ratio is its reciprocal; \( ER = 3.84 \). Figure 16 shows that this ratio varied slightly across the speed range of the wind tunnel and also shows a reduction in the energy ratio due to the installation of the vortex generators. This reduction was largely caused by the high induced drag of the vortex generators.
It can also be seen on the figure that the maximum test section velocity was reduced from 204 to 202 ft./sec. The maximum speed varied slightly from day to day, chiefly because of small changes in the line voltage to the electric drive motor, and sometimes went as low as 199 ft/sec. It is quite likely that the loss in speed could be recovered or even turned into a gain by adjusting the shape, size and location parameters of the vortex generators. For example, it was originally planned to make the angle of attack variable in this installation in order to optimize the performance with respect to this one parameter, but difficulties arose in attaching the seven pairs of airfoils to the surface of the transition from a circular to an octagonal passage. Each airfoil had to have its attachment points fitted to the local surface contours, so that a variable angle of attack feature would have been quite troublesome. Fortunately, the configuration chosen for testing caused a barely significant loss in speed but a sharp improvement in speed steadiness, so that it was not considered to be worthwhile to investigate other configurations.

Notwithstanding the variations in line voltage, the loss in speed for a given input power can be estimated from the energy ratio relationship.

\[ \text{ER} = \frac{\frac{1}{2} \rho A_0 V_o^3}{550 \eta \text{BHP}} \]

Assuming constant fan efficiency, \( \gamma \), \( V_o = k \sqrt[3]{\text{ER}} \)

Then

\[ \frac{\Delta V_o}{V_o} = \frac{1}{3} \frac{\Delta \text{ER}}{\text{ER}} \]

From Fig. 15, the change in energy ratio at 200 ft./sec. is about 0.1 in 3.8 so that

\[ \frac{\Delta V_o}{V_o} = \frac{1}{3} \cdot \frac{0.1}{3.8} = 0.009 \]

i.e., less than 1%, or about 2 ft./sec. at the highest speed. Conversely, too, this relation shows that if one wanted to realize truly significant gains in speed capability, the energy ratio would have to be greatly improved.
5.3 Diffuser Pressure Recovery

The pressure recovery characteristics of the fourth diffuser were determined by measuring the static pressure difference between the fan-and-straightener discharge at station C and the settling chamber pressure, i.e., the pressure just ahead of the contraction cone. This latter station was chosen because it was considered that the flow immediately at the diffuser exit would be too unsteady to yield meaningful results. The measurements of the 'diffuser pressure rise', then, also include the losses in the third and fourth corners and the turbulence screens, however, changes in the actual pressure recovery through the diffuser would still be indicated by changes in the measured pressures.

Denoting the diffuser pressure rise by \( \Delta p_D \), Fig. 17 shows individual values of the ratio \( \Delta p_D / q_0 \) plotted against \( V_o \) before and after the installation of the vortex generators. This ratio, which may be called the diffuser pressure rise coefficient, improved slowly with increasing speed, and was relatively unaffected by the vortex generators, indicating again that their drag approximately offset the benefits from maintaining attached flow.

5.4 Fan Speed

Another indicator of wind tunnel performance is the fan RPM required to produce a given air speed through the wind tunnel test section. For the University of Toronto low speed wind tunnel this was first measured by Laundry in 1954 (Ref. 11). He found that the relation was linear with a slope of 0.354 ft./sec./RPM. Subsequent to his work, however, turbulence screens have been installed in the wind tunnel settling chamber, increasing the losses.

Fan RPM is not included in the wind tunnel instrumentation, but a simple method was devised to yield the necessary data. A razor blade was magnetized and then taped securely to the face of one of the fan blades with the magnetic axis directed radially. A flat coil of some 75 turns of fine transformer wire was taped onto the wall of the wind tunnel in the plane of the fan. Each time the magnetized razor blade swept past the coil a sharp voltage spike of one to two volts appeared across the terminals of the coil. This electrical pulse was sent over the existing trunk lines to the PACE 221R analog computer where it was scaled down and plotted on the Honeywell 1508 Visicorder, a high-frequency response, optical oscillograph. Simultaneously a sine wave of known frequency was plotted on a second channel of the Visicorder. The fan RPM was then found by counting the spikes from the pick-up coil and the cycles of the sinusoid on the same strip of paper. Figure 18 shows the results so obtained before and after the installation of the vortex generators. For test section speeds above 70 ft./sec., the fan RPM was about one to two percent higher than previously. For comparison also, Laundry's results are shown on the figure.
5.5 **Wind Tunnel Turbulence Factor**

The wind tunnel turbulence factor was measured near the middle of the speed range using the "pressure sphere" technique described in Ref. 9. The vortex generators did not have a very significant effect; the turbulence factor decreased from 1.21(4) to 1.20.

5.6 **Diffuser Boundary Layer Profiles**

Further investigation into the effects of the vortex generators was carried out by repeating the measurements of the diffuser boundary layer profiles. Figure 19 shows the velocity profiles at stations 80, 90, 100, 110 and 120. For comparison, the earlier profiles of Fig. 6 are also shown in broken lines. Whereas the "before" profiles showed a rapidly deepening region of separation, the new profiles are all attached and quite "full". As before, these profiles correspond to the maximum wind tunnel speed. Their 'S' shape indicates that there has been an interchange of velocity energy between the upper and lower parts of the original profiles. The region near the surface has been re-energized and a velocity deficit appears several inches away from the surface.

The design of the vortex generator installation was determined by the location of the separation point and by the shape of the diffuser boundary layer profiles with the wind tunnel running at maximum speed. This most likely accounts for the resulting steadiness and energy ratio being best at the high speeds and deteriorating at speeds below about 100 ft./sec. Attempts were made to determine if separation still occurred in the low speed range, but the dynamic pressure was too small (2 to 3 millimeters of water in the free stream) to give usable data above the noise in the electronic equipment.

**CONCLUSIONS**

An array of vortex generators designed according to recommendations in the literature and installed in the wind tunnel fourth diffuser reduced the wind tunnel speed unsteadiness such that the RMS value of the speed fluctuations is now approximately 0.30% of the mean at low speeds and less than 0.07% of the mean at high speeds.

The improvement in speed steadiness is attributed to the elimination of flow separation in the diffuser.

The drag of the vortex generator installation has reduced the wind tunnel energy ratio by about 3%, and the maximum test section speed by about 1%. This loss in speed could possibly be recovered by
re-installing the vortex generators at a slightly lower angle of attack to reduce their induced drag, but the speed steadiness would have to re-examined.

The wind tunnel turbulence factor was lowered, but not by a significant amount.
# References


Boundary Layer Measurements

As shown in Sec. IV, the selection of the system of vortex generators was determined primarily from information about the boundary layer ahead of and in the neighborhood of the separation region. A probe was designed to produce this information in a rapid, graphic manner.

The probe, Fig. 20, is a thin strut approximately twelve inches high from which twenty-two total pressure tubes extend forward into the stream. Pressure from each of these tubes is lead through flexible tubing within the strut to the Scanivalve assembly mounted on the aft portion of the strut base. As shown in the schematic diagram, Fig. 21, the Scanivalve assembly contains a motor-operated rotary valve which directs the pressure inputs sequentially to a Statham strain gauge pressure transducer which is also housed within the assembly. Six electrical leads connect the assembly to a remote station where the transducer output is monitored and power is provided for motor operation and strain gauge excitation. In the present application the output was amplified 1000 times on an Offner 492 DC amplifier, then passed over existing trunk lines to the PACE 221R analog computer where it was further amplified, filtered for noise and appropriately scaled for plotting on a PACE 1100 X-Y plotter. The motor on/off switch shown on the schematic diagram was an existing switch on the computer console.

The graph thus obtained was a profile of dynamic pressure plotted against the distance into the stream from the surface to which the probe was attached. This distance was displayed accurately to scale through the particular choices of probe positions and Scanivalve channels. The reference pressure for the pressure transducer was chosen to be that from the lowest pitot tube on the probe. This tube rested on the surface, and being only 0.050" diameter it received negligible dynamic pressure for such deep boundary layer profiles and thus registered essentially only the local static pressure. This pressure was continuously applied to one side of the pressure transducer and all the pressures, including this one, were applied in sequence to the other side. The "zero" for the pressure signals was then simply the signal produced when the Scanivalve was sampling the bottom pitot tube, for then there was no pressure difference across the transducer.

Figure 22 is an actual profile obtained in this manner. It is interesting to note that the pressure transducer used in this testing was designed for a working pressure range of $\pm$ 2.5 psi (a range of 760 psf) whereas the dynamic pressure corresponding to the largest displacement
in Fig. 22 was only about 12 psf, less than 2% of the range of the transducer, yet the signal is quite adequate for giving good, quantitative information about the boundary layer. This particular profile is from the side wall of the first diffuser, approximately ten feet downstream from the test section. It shows a boundary layer some six to eight inches thick with a fairly steep gradient at the surface. This was one of the first profiles to be measured and it helped to confirm that unsteadiness and separation problems did not arise in the first diffuser.

Most of the "hash" or noise in the plotted profile is due to actual fluctuation in the measured pressures and to stray signals from the motor control lines or from the motor itself in the Scanivalve assembly. This noise became important in examining the boundary layer in the fourth diffuser where even the free stream dynamic pressure was very weak. The boundary layer profiles presented in Figs. 6 and 19 were obtained by averaging the results of several repeated runs in order to reduce the scatter, but station 120 appeared to be the practical limit of this method because of the rapidly diminishing speed of the air through the diffuser.
Fig. 1  WIND TUNNEL AERODYNAMIC OUTLINE
Figure 2
Fourth diffuser stations diagram.
Figure 3
Composite photograph from moving picture films showing view looking up-stream through fourth diffuser. Wool tufts show that the flow along the left half of the floor and part of the left wall is reversed.
Figure 4

A vortex-generating airfoil mounted on a surface. The core of the vortex is released just inboard of the tip, at about the edge of the boundary layer.
Figure 5

Plan view of an array of airfoils generating vortices of alternating sign.
Figure 6

Boundary layer velocity profiles on the floor of the fourth diffuser before the installation of the vortex generators.
Separation occurs at about station 95.
Figure 7

Boundary layer velocity profiles at stations 20 and 40. The vortex generators were later installed at station 27 using these profiles to determine the required dimensions.
Figure 8
Flat development of wind tunnel wall showing vortex generator configuration with respect to straightener vanes. The vortex pairs sweep the wakes of the vanes up from the confining surface.
Figure 9

Prototype wooden vortex generator. The airfoil section is NACA 64,812, $\alpha = 0.3$
Figure 10

Production metal vortex generators.
Figure 11

Vortex generators installed in wind tunnel transition duct.
Dynamic pressure, mm water

Figure 12

Typical time history of test section dynamic pressure before vortex generators were installed in the wind tunnel fourth diffuser.
Comparison of test section dynamic pressure histories at maximum speed before and after vortex generators were installed.
Comparison of test section dynamic pressure histories at 90 ft/sec before and after vortex generators were installed.
Figure 15

Variation of the steadiness parameter $\sigma_u/V_0$ with test section dynamic pressure before and after installation of vortex generators.
Figure 16

Variation of wind tunnel Energy Ratio, ER, with test section speed before and after vortex generators were installed in the fourth diffuser. The vortex generators decreased the Energy Ratio by 2 to 3%.
Figure 17

Diffuser pressure rise coefficient vs. test section speed
Figure 18

Wind tunnel test section speed vs. fan RPM before and after installation of vortex generators.
Figure 19
Comparison of diffuser boundary layer profiles before and after installation of vortex generators at station 27. The earlier profiles are shown in broken lines. The tips of the vortex generators are 5½ inches from the surface.
Figure 20

Boundary layer probe and Scanivalve assembly. The lower figure shows the internal tubing. The assembly is approximately 12 inches high.
Figure 21

Schematic diagram of boundary layer profile measuring equipment. The computer-produced time base gives vertical dimension to the output profile to correspond to the height of the actual profile.
Figure 22

Sample output plotted by boundary layer profile measuring equipment. Approximately zero dynamic pressure is indicated wherever unused Scanivalve channels are being sampled. True zero is shown at the lowest position.