LOSS PRODUCTION IN THE WAKE OF A SIMULATED SUBSONIC TURBINE BLADE

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ABSTRACT
The time-averaged flow in the wake of a model of a turbine blade was surveyed using a three-hole pressure probe; boundary layer traverses were also carried out using a flattened pitot probe. Loss coefficients were derived from the mass-weighted deficit in stagnation pressure. Results showing the progression of loss with streamwise distance along the surface and the wake of the model are presented. It was found that the loss generated in the wake comprised one-third of the profile loss when a well-developed vortex street was present in the wake. This proportion was reduced by increasing the thickness of the suction surface boundary layer, and by simulating the deviation that occurs in a real turbine blade. In both cases the strength of the vortex street was also shown to have been reduced.

NOMENCLATURE

- \( c_p \) specific heat capacity (at constant pressure)
- \( C_{p,b} \) base pressure coefficient
- \( c \) plate chord
- \( f \) vortex shedding frequency
- \( m \) mass flow rate
- \( p \) pressure
- \( Re \) Reynolds number (based on plate chord)
- \( s \) surface coordinate, measured from trailing edge, or entropy
- \( St \) Strouhal number
- \( T \) temperature
- \( t \) trailing edge thickness
- \( U \) freestream chordwise velocity
- \( u \) local chordwise velocity
- \( V \) velocity magnitude
- \( x \) chordwise coordinate
- \( Y_c \) local stagnation pressure loss coefficient
- \( Y_\theta \) potential stagnation pressure loss coefficient
- \( y \) pitchwise coordinate
- \( \delta' \) displacement thickness
- \( \epsilon \) stagnation pressure loss, or energy, thickness
- \( \mu \) dynamic viscosity
- \( \rho \) density
- \( \theta \) momentum thickness
- \( \theta_p \) contribution to momentum thickness from pressure deficit

Subscripts
- \( b \) base conditions
- \( c \) test section exit
- \( fs \) freestream conditions
- \( in \) test section inlet
- \( o \) stagnation conditions
- \( s \) suction surface
- \( 1 \) plane just upstream of trailing edge
- \( 2 \) plane at 140% chord
- \( 5 \) integration extent of boundary layer or wake

INTRODUCTION
Advances in computer power and in numerical techniques are continuing to improve the capability of computational fluid dynamics to model the turbomachinery flowfield. Blade rows can now be meshed in three dimensions with sufficient refinement to resolve tip clearance and endwall flows in detail. Thanks to this improved understanding, modern designs are being produced with significant reductions in the loss associated with such regions, such that total-to-total efficiencies above 90% can now be achieved in many types of machine. However, while the contribution from these flows to the overall loss has been reduced, that of other areas has remained relatively unchanged. This is particularly true of the trailing edge...

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flowfield, where no significant loss reductions have been achieved for some years. Denton (1993) estimates that wake loss, defined as the component of profile loss created in the blade wakes, typically comprises about 10% of the aerodynamic loss in current turbine designs.

In order to reduce the wake loss, a better understanding of the processes which are responsible for its creation must be sought. Wake flows in turbomachinery applications have been well studied, and the basic flow features are well known. However, although the kinematics of the wake - namely, the von Kármán vortex street, turbulence characteristics and the time-averaged velocity profiles - have been thoroughly investigated, the issue of loss creation is seldom addressed.

One of the most thorough experimental investigations of a trailing edge flowfield was carried out by Paterson and Weingold (1984). Using LDV (laser-doppler velocimetry) to measure mean and fluctuating velocities behind a flat plate simulating a compressor blade, they ascertained the presence of a vortex street in the wake. They also discovered that, by using a splitter blade to suppress vortex shedding, the base pressure was increased. A control volume analysis of the wake from trailing edge plane to fully mixed-out conditions, such as presented by Denton (1993), shows that this is equivalent to a reduction in wake loss. The vortex street is clearly responsible for at least part of the loss created. However, as control volume analyses provide only global information, it is not possible to find out at what point in the wake the loss is being generated.

In a subsequent paper describing the effect of loading on the model, McCormick, Paterson and Weingold (1988) showed that the wake momentum thickness (which is a measure of the amount of loss creation) increased sharply just behind the trailing edge when a vortex street was present. The distance over which this increase was most rapid corresponded to the region in which formation of the vortex street had been shown to occur in the earlier paper. This suggests that the formation of the vortex street is the primary loss-producing mechanism in the wake. A similar result was found by Ravindranath and Lakshminarayana (1982) behind a compressor rotor, although they made no comment on the presence or otherwise of a vortex street.

The information in the literature on the effects of boundary layer characteristics on wake loss is too scarce to allow definitive conclusions to be drawn. In a series of measurements on the flow behind a flat plate, Sieverding and Heinemann (1990) found that a change in boundary layer state from turbulent to laminar at the trailing edge only increased the base pressure by about 2% of the local dynamic head, despite a 28% increase in the vortex shedding Strouhal number. Paterson and Weingold (1984) detected no change in base pressure or in mean velocity wake profiles when the plate boundary layers (in all cases fully turbulent) were thickened on one side and thinned on the other by about 20%. A comparison with the results from McCormick et al. (1988) also showed that there was no difference in the base pressures behind the flat plate and the lightly loaded plate. However, in a comparison between two compressor cascades with significantly different trailing edge thicknesses, Hobbs et al. (1982) found that vortex shedding did not occur in the wakes of the profile with a higher ratio of boundary layer thickness to trailing edge thickness. No information was presented for either base pressure or loss, so it is not known if this was accompanied by a reduction in loss.

The above paragraphs indicate a need for further investigation of wake loss, especially in turbine blades. The present investigation has two objectives. The first is to measure the rate at which loss is generated in a wake typical of a turbine blade. The second is to attempt to clarify the relation between boundary layer characteristics and wake loss.

**SCOPE OF INVESTIGATION**

The investigation was limited to two-dimensional, incompressible flow and it was decided to measure the flow around a simulated trailing edge flow-field, as was done by McCormick et al. (1988). This was done for two reasons: it permitted a more detailed examination of the flow by increasing the scale of the geometry, and it enhanced the possibility of boundary layer manipulation without the need for extensive alteration of blade profiles. The details of the experimental apparatus are described in more detail in the next section.

It was decided to concentrate the investigation on the time-averaged flow in the wake. Although the presence of an unsteady von Kármán vortex street was expected, to dwell on its details would detract from the main emphasis of the investigation, namely the time-averaged rate of loss creation.

The most meaningful definition of loss in turbomachinery, from a physical point of view, is mass-averaged entropy creation (Denton, 1993). Entropy can be calculated from any other two thermodynamic properties of the fluid; most commonly stagnation pressure and temperature are used. For small changes in temperature and pressure, in particular in flows where compressibility is negligible, this relationship can be expressed as:

\[
T_s \int s dh = c_p \int T_d dh - \frac{1}{p_0} \int p_d dh
\]

(1)

It is well known that unsteady changes of stagnation temperature occur in the unsteady vortex street (Kurosaka et al., 1986). However, the First Law of Thermodynamics states that, when mass-averaged, the flux of stagnation enthalpy must remain constant in an adiabatic flow. Consequently, regardless of the presence of such fluctuations, the mass-averaged rate of entropy creation within a control volume (which is equal to the net efflux of mass-averaged entropy in an adiabatic flow) can be expressed in terms of the change in mass-averaged flux of total pressure alone. This is not to say that the total temperature fluctuations are not linked to the processes by which the entropy is created locally; it merely asserts that knowledge of the total temperature field is unnecessary for calculating the global entropy creation.

Three series of tests are reported in this paper. The first of these investigates the increase in loss through the test section, from the blade leading edge to the far downstream wake. The second investigates the effect of suction surface boundary layer thickness on the magnitude of the wake loss. The third investigates the effect of altering the deviation angle of the exit flow.
Station 1

EXPERIMENTAL FACILITY

Model Geometry and Situation

The model used for the experiments was a flat wooden plate with semicircular leading and trailing edges. It was situated in the test section depicted in Fig. 1. The surfaces of the test section above and below the plate were constructed from flat wooden sections connected by thin metal sheets. The effect of the change in flow area between these surfaces and the model was to produce a plate pressure distribution representative of that around a turbine blade. The downstream portion of the test section, which exhausted to atmosphere, was 300mm high. The plate itself was 725mm long, 455mm wide and 14.5mm thick, thus having a chord-to-trailing edge thickness ratio and trailing edge blockage (defined as trailing edge thickness to test section height) representative of a low pressure gas turbine blade.

The test section was separated from the wind tunnel exit by a 4mm gap. This isolated the test section from vibrations of the wind tunnel wall, and also (due to the pressure differential across the gap) bled off some of the fluid in the wall boundary layers at entry to the test section.

Test Conditions

The Reynolds number was 7.3x10^5 at the datum condition. This is typical of a high or intermediate pressure aircraft engine turbine blade or a low pressure gas turbine blade. Reynolds numbers are rather less than this (2x10^5) for low pressure aircraft engine blades but it was found that, as long as the state of the boundary layers did not change, Reynolds number did not have a significant influence on the results. Reynolds number is defined as:

\[ \text{Re} = \frac{\rho V_e c}{\mu} \]  

where \( V_e \) is the isentropic exit velocity, is:

\[ V_e = \sqrt{\frac{2}{\gamma} (P_{\text{in}} - P_{\text{d}})} \]  

Atmospheric pressure was equated to \( P_{\text{d}} \). The above Reynolds number corresponds to an exit velocity of approximately 15.5 m/s and an exit Mach number of less than 0.05. The inlet freestream turbulence was of the order of 0.5%.

Instrumentation

Surface pressure tappings were drilled along the centreline of both sides of the plate at 10% chord intervals. An additional tapping was fitted 20mm from the leading edge. A brass insert containing fifteen tappings on either side, and one tapping on the centreline, was incorporated in the trailing edge. This enabled detailed measurements of the pressure distribution over the last 1.5 trailing edge thicknesses of the plate surface to be performed.

Two flattened pitot probes, of thickness 0.35mm and 0.53mm, were used to traverse the plate boundary layers. Access to the test section was provided through a slot in the tunnel wall above the plate. The 0.53mm probe was of conventional design; the other was of a 'hook' design, and was employed for one-off traverses just upstream of the trailing edge with access from the opposite side of the plate. When more than one such traverse was needed, the test section was inverted and the conventional probe used.

The wake was traversed using one of two three-hole pressure probes. of the 'Neptune' and 'cobra' designs. The Neptune probe had a width of 4.0mm; its three tubes, each of diameter 0.8mm, were aligned in the spanwise direction. Adjacent tubes were separated by a small gap, to minimise interference. The cobra probe had a width of 2.7mm; its tubes (of diameter 1.0mm) were aligned in the pitchwise direction. Both of these probes are small relative to the wake thickness and to the size of the shed vortices. Measurements of time-averaged pressure in an unsteady flowfield are notoriously difficult, and the two probes produced slightly different results. Comparisons are only made between results derived from measurements taken with the same probe.

All traverse probes were driven by a stepper motor with a positional accuracy of 0.01mm. The traverse plate was offset 33mm from the centreline to prevent disturbance of the pressure field around the pressure tappings. The access slots were fitted with draught excluder to minimise flow leakage to or from the test section.

Vortex shedding frequency

The pressure fluctuations produced by the vortex street are audible to the human ear. Its frequency could thus be found using a stethoscope positioned just downstream of the trailing edge. The clear tone was compared aurally to the output from a sine-wave generator connected to a loudspeaker located outside of the tunnel. The pitch of this tone was varied until the two frequencies were close enough to discern the beat frequency, which was used to hone the tuning further. The accuracy of this method is estimated to be ±1% for near pure-tone vortex shedding.

Flow visualisation

The vortex street was visualised using a smoke-and-strobe method. The smoke injection probe was inserted a little way upstream of the leading edge, and could be tilted in the pitchwise direction. The smoke plume was thereby directed to pass either above, below or around both
sides of the leading edge, into the corresponding plate boundary layers and the sides of the vortex street. The smoke in the wake was illuminated by a strobe to reduce the vortex street pattern, and photographed through the perspex side of the test section.

**Data processing and presentation**

Boundary layer traverse measurements were processed to give velocity profiles; wake traverse measurements were processed to give static pressure, axial velocity and pitchwise flow angles. Boundary layer and wake thicknesses were calculated using the following definitions:

\[
s^* = \int \left(1 - \frac{u}{U}\right) dy
\]

\[
\theta = \int \left(\frac{p_{w} + p_{w}U}{\rho U^2} - \frac{p + p_{w}^2}{\rho U^2}\right) dy
\]

\[
\varepsilon = \int \frac{u}{U} \frac{p_{w} - p_{w}}{\rho U^2} dy
\]

In regions where static pressure does not vary with pitchwise coordinate (such as in the boundary layers), these simplify to the conventional definitions of displacement, momentum and kinetic energy thicknesses respectively. Two loss coefficients were derived from the second and third integral parameters. The first corresponds to the mass-averaged stagnation pressure loss of the flow through the measurement traverse plane, non-dimensionalised by \(\frac{1}{2}p'U'i\). This is referred to as the **local loss coefficient**, and is given the symbol \(Y'\). A straightforward manipulation of Eq 6 shows that:

\[
Y' = \varepsilon \left(\frac{U}{V_r}\right)^3
\]

The second coefficient is equal to the sum of \(Y'\) and the additional loss (suitably non-dimensionalised) which would be created were the flow to mix out at constant area to a uniform flow. This coefficient, given the symbol \(Y''\), is called the **potential loss coefficient**. It can be shown, using a control volume analysis, to be given by:

\[
Y'' = \frac{2\theta}{t} \left(\frac{U}{V_r}\right)^3
\]

The significance of these definitions will be discussed later. It should be noted however that the integrals are non-dimensionalised by the trailing edge thickness rather than the passage width. This is because we are concerned with the loss per trailing edge rather than the loss per unit mass flow. In order to convert this magnitude to a more familiar value (based on the mass flow through a blade passage), it is suggested that the reader multiply the loss coefficients presented by the trailing edge thickness in a typical cascade, say 0.03. For example, a reported loss coefficient of 0.4 is equivalent to a 'standard' loss coefficient of 0.02.

The base pressure \(p_b\) was defined as the pitchwise-averaged pressure over the trailing edge. A corresponding base pressure coefficient was defined as:

\[
C_{pb} = \frac{(p_b - p_i)}{\frac{1}{2}\rho U_i^2}
\]

This is defined relative to the surface pressure just upstream of the trailing edge rather than the downstream pressure, as this definition is used in a subsequent control volume analysis. The vortex shedding frequency \(f\) was non-dimensionalised to produce a Strouhal number, defined as:

\[
St = \frac{f(t + \delta_i)}{U_i}
\]

Positions were non-dimensionalised by either plate chord with the leading edge as origin, or the trailing edge thickness with the trailing edge as origin. (The ratio of chord to trailing edge thickness was chosen to be exactly 50, to facilitate conversions from one scale to the other.) Pitchwise direction was defined positive from the plate centreline to the pressure surface.

**Measurement Repeatability and Reliability**

The *repeatability* with which the dimensionless quantities listed above could be measured was determined by comparing the processed results of a number of measurements taken at identical positions and flow conditions. Typical error margins for each are:

- Wake traverse loss coefficients: \(\pm 0.003\)
- Boundary layer loss coefficients: \(\pm 0.001\)
- Base pressure coefficient: \(\pm 0.005\)
- Strouhal number: \(\pm 0.005\)

To determine the measurement *reliability* is more difficult. Of greatest concern is the effect of the vortex street on the readings from the pressure probes. Lewis (1993) summarises the causes of

![Figure 2. Surface Pressure Distribution](image-url)
A test program was used to evaluate the constancy of the potential loss coefficient. The potential loss, as defined by Eq. 8, must be constant in order to minimize the second source of error. The remaining issue of flow incidence is not resolvable. The magnitude of the resulting inaccuracies in such flow conditions as: inadequate probe response time, differences between the time-averaged pressure and the probe equilibrium pressure, and unsteady incidence effects. Using the formula suggested by Lewis, it was found that the probe response time was at most 1/60 of the vortex shedding period and hence the probe response should be quasi-steady. His recommendations were also followed to minimize the second source of error. The remaining issue of flow incidence is not resolvable. The magnitude of the resulting errors however can be gauged by examining the progression of the potential loss in the wake. By considering a suitable control volume, it can be shown that the potential loss defined in Eq. 8 must be constant in the wake, provided that the flow is not accelerating or decelerating. The constancy of the potential loss coefficient was used as a test for the accuracy of the probe readings.

A. PROGRESSION OF PROFILE LOSS

Test Program

The suction surface boundary layer was traversed at stations from 30% chord to 99% chord. The pressure surface boundary layer was similarly traversed between 70% and 99% chord. The wake was traversed from 101% to 140% chord, using the Neptune probe. Surface pressures were measured along the plate and in detail around the trailing edge. The vortex shedding frequency was also measured.

Pressure Distributions

The pressure distribution over the whole plate is presented in Fig. 2. The loading is typical of a moderately-loaded turbine blade, with a strong acceleration towards the rear of the pressure surface and a weak deceleration over the rear half of the suction surface. The low pressure either side of the leading edge suggests that there is a large separation bubble on both surfaces. This leads to early transition in both boundary layers, as was verified using oil-and-dye flow visualisation.

The pressure around the trailing edge is presented in detail in Fig. 3. The influence of the trailing edge flow on the pressure distribution extends some distance upstream, slightly further than can be determined from the data. It is useful to determine a point on the surface where trailing edge effects start to become significant. Based on the evidence from the above pressure distribution, and results from Sieverding and Heinemann (1990) and Paterson and Weingold (1984), a position two trailing edge thicknesses upstream of the end of the trailing edge (96% chord) was chosen as a suitable position. The average of the two pressures on either side, $p_i$, and the corresponding freestream velocity $U_i$, were used as reference quantities for the definition of base pressure and Strouhal number.

The difference in pressure between the suction side and pressure side at the trailing edge blend point indicates the effect of boundary layer thickness. The thinner pressure surface boundary layer produces a lower trough in pressure, due to the higher velocity in the part of the flow affected by streamline curvature close to the surface. Once the blend point is reached, the pressure rises up to the point where the boundary layer separates: this occurs about 22° around the semicircle for both boundary layers, despite the difference in their thicknesses. After the boundary layer separation, there appears to be a small loading effect around the inner 90% of the base, which suggests that the shear layers either side are turned slightly toward the suction side of the centreline. The base pressure coefficient, averaged over the pitchwise projection of the base, is equal to -0.088. This is rather higher than the typical value of -0.15 suggested by Denton (1993).

Boundary Layer Characteristics

The boundary layer characteristics at 96% chord are presented in Table 1. The ratios of boundary layer thicknesses to trailing edge thickness are typical of uncooled turbine blades. The relatively high shape factor of the pressure surface boundary layer suggests that it has begun to relaminarise under the influence of the strong favourable pressure gradient. A comparison of the boundary layer thicknesses reveals that the suction surface boundary layer is about 5.3 times thicker than the pressure surface boundary layer. This is realistic for a turbine blade of similar loading.

<table>
<thead>
<tr>
<th>Table 1 Boundary Layer Parameters at 96% chord.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>$\delta''h$</td>
</tr>
<tr>
<td>$\theta''/h$</td>
</tr>
<tr>
<td>$\zeta/h$</td>
</tr>
<tr>
<td>$\delta''/h$</td>
</tr>
</tbody>
</table>

Vortex Shedding

The pressure and suction sides of the vortex street are illustrated in Fig. 4. The vortices emanating from the pressure surface boundary layer entrained in the street. The suction side vortices, in contrast, are ill-defined, and the remains of the shear layer on the outside of the wake...
indicates that not all of the suction surface shear layer is involved in the vortex formation. This reflects the difference in thickness between the boundary layers at separation. A similar difference in the vortex rows was reported by Han and Cox (1983) behind a turbine cascade.

The shedding frequency was found to be 252Hz, which corresponds to a Strouhal number of 0.281. This is very similar to the values measured by Steverding and Heinemann (1990) with one turbulent and one laminar boundary layer at the trailing edge of an unloaded plate.

Stagnation Pressure Loss

The two loss coefficients are plotted against chordwise position in Fig. 5. The loss produced in the suction surface boundary layer alone is plotted from 30% chord, and from 70% chord the aggregate loss from both boundary layers is also shown. The most obvious feature is the sudden increase in loss within the first 5% chord (2.5t) downstream of the trailing edge. It is not possible to quantify the loss increase in this region, as the subsequent fall in potential loss indicates that the values are not reliable close to the trailing edge. This is a consequence of the probe measurement errors caused by the very high flow unsteadiness. However, from 120% chord the potential loss coefficient is constant. Since the freestream velocity was also observed to be constant downstream of this station, it can be assumed that the measurement errors are restricted to the flow before this station, i.e. to the first ten trailing edge thicknesses downstream of the trailing edge.

The definition of wake loss can be made in three slightly different ways. The first definition corresponds to the difference between the potential loss in the wake (to allow full constant-area mixing of the wake to occur) and the local loss just upstream of the trailing edge. However, it can be reasoned that, if the boundary layers mix out at the local flow area, the associated loss is independent of the nature of the wake flowfield and should not be included in the definition of wake loss. Following this argument, wake loss is defined using the potential loss upstream of the trailing edge. A third definition arises if it is assumed that, due to the presence of a downstream blade row, complete wake mixing will not be achieved. Wake loss is then defined using the local loss at some downstream station to be specified. These three definitions were used to calculate the increase in loss between the stations at 96% and 140% chord (omitting the mixing loss of the boundary layers in the third). These two positions are referred to as Stations 1 and 2 respectively; hence the three definitions refer to the differences \( (Y_{e2} - Y_{e1}) \), \( (Y_{e2} - Y_{B1}) \) and \( (Y_{e2} - Y_{B1}) \). The ratios of these loss increases to the total profile loss \( Y_{e2} \) are 41%, 33% and 27% respectively. The view of the authors is that the second definition is the most physically sound; therefore one third of the profile loss is produced in the wake. Values of wake loss quoted elsewhere in this paper are calculated using this definition, unless stated otherwise.

The difference in loss coefficients \( (Y_{e2} - Y_{B1}) \) at any station corresponds to the loss created as the local wake profile mixes out to uniform conditions. Expressed as a percentage of the wake loss \( (Y_{e2} - Y_{B1}) \), 22% of the loss has yet to be created at 120% chord, and 16% at 140% chord. This illustrates that the rate of mixing is relatively slow after 120% chord, and also that over three-quarters of the loss has been produced within the first ten trailing-edge thicknesses of the wake.

Discussion

Denton (1993) derived a relationship between the stagnation pressure loss of a cascade of flat plates with zero stagger, the base pressure and the boundary layer integral parameters at the trailing edge. Expressed in terms of parameters derived in this paper, the equation approximates to:
Loss coefficient as a function of x/Chord for Tests 1, 2, and 3.

Figure 6. Streamwise Progression of Loss Coefficients: Effect of Suction Surface Boundary Layer Thickness

Figure 7. Potential Loss Coefficient vs. Suction Surface Boundary Layer Momentum Thickness

\[ \phi = \frac{1}{\gamma} \left( \frac{C_{p}}{t} - \frac{\delta_{l}}{t} \right) \]

where \( w \) is the pitch of the cascade in the original equation. Although the experimental arrangement is not a cascade, it is informative to compare the loss calculated from the above equation with the loss measured in the wake. The width of the test section exit is used as the value for the cascade pitch.

The three contributions to loss on the right hand side of Eq. 11 are 0.318, 0.088, and 0.074 respectively, giving a total loss of 0.480. The measured value (scaled accordingly) is 0.527. The difference amounts to about 9% of the measured loss. This error arises from a number of factors, including experimental error and pitchwise variations in the trailing edge plane. It is useful to compare the relative magnitudes of the loss components derived from the equation, which correspond respectively to the boundary layers, the base drag on the plate, and the deceleration due to trailing edge blockage. The sum of the last two terms constitutes the wake loss. The last term is higher than is normally assumed, contributing almost as much as the base pressure term to the wake loss. The wake loss comprises about one third of the total, as was found using the experimentally determined coefficients.

B. EFFECT OF SUCTION SURFACE BOUNDARY LAYER THICKNESS

Test Program

A series of tests was performed in which the thickness of the suction surface boundary layer was altered. In Test 1, the decelerating passage over the suction surface was replaced with one of constant area, with the exit area unchanged. This change reduced the boundary layer momentum thickness to half of the value in the datum arrangement discussed previously (referred to in this section as Test 2). The boundary layer was also thickened (having replaced the original wall section) using cylindrical rods glued to the plate surface. Three combinations of rods were applied. In Test 3, a 2.0mm diameter rod was glued onto the suction surface at 25% chord. In Test 4, an additional rod of 1.7mm diameter was glued at 45% chord; this was replaced in Test 5 by a 3.2mm diameter rod at the same position.

The series of measurements taken at each arrangement were identical to those for the test series discussed above.

Boundary Layer Characteristics

Table 2 presents the suction surface boundary layer characteristics at 96% chord, for all five tests. The shape factor is seen to vary slightly, but in all cases the boundary layer is fully turbulent.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>( \delta/t )</th>
<th>( \theta/t )</th>
<th>( \delta^\circ/\theta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.104</td>
<td>0.074</td>
<td>1.41</td>
</tr>
<tr>
<td>2</td>
<td>0.200</td>
<td>0.135</td>
<td>1.47</td>
</tr>
<tr>
<td>3</td>
<td>0.247</td>
<td>0.169</td>
<td>1.46</td>
</tr>
<tr>
<td>4</td>
<td>0.331</td>
<td>0.225</td>
<td>1.47</td>
</tr>
<tr>
<td>5</td>
<td>0.393</td>
<td>0.278</td>
<td>1.41</td>
</tr>
</tbody>
</table>

Stagnation Pressure Loss

The variation of potential loss coefficient \( \phi \) with chordwise position through the test section is presented in Fig. 6, for Tests 1, 2, and 3. The continuous fall in loss in the wake in Test 1 indicates that the flow is too unsteady to produce reliable results. This suggests that the vortex street is invigorated by the reduction in suction surface thickness. Conversely, the measured loss coefficient in Test 3 reaches a constant value much earlier, suggesting that the vortex street is less vigorous. The local loss coefficient \( \phi \) for this test is also included in
behind a cylinder - was exploited to test this hypothesis. As there can be no pitchwise pressure gradient in a steady wake, this deficit can only be attributed to an unsteady phenomenon, namely the vortex street. Hence the extent to which the pressure is depressed can be used to gauge the strength of the vortex street. As a measure of this deficit, the percentage contribution of the pressure deficit to the momentum thickness (defined in Eq. 5) was calculated at Station 2. This is shown in Fig. 8, from which it is clear that there is indeed a reduction in vortex shedding amplitude. This trend can be understood in the light of Fig. 4, the smoke visualisation of the suction side vortex row. The suction surface boundary layer is not completely entrained into the vortex formation region, and this effect will become more significant as the thickness of the boundary layer increases. Although a smaller proportion of the fluid is involved in the vortex street, this does not preclude a rise in the total production of wake loss, which is also a function of the boundary layer blockage at the trailing edge. Nevertheless, it is expected that at a high enough ratio of suction surface boundary layer thickness to trailing edge thickness, the vortex street will be fully suppressed. The sharp reduction in pressure deficit in Test 5 suggests that this condition is imminent. This conclusion applies only to boundary layers that are still attached at the trailing edge. The case of a blade with a separated suction surface boundary layer has not yet been investigated but is thought likely to increase the intensity of vortex shedding.

C. EFFECT OF DEVIATION

Test Program

A series of tests was performed to investigate the effect of imposing flow deviation on the wake flowfield. This was achieved by altering the inclination of the two exit panels. The construction of the test section allowed the position of the panels to be altered without changing the upstream flow passages. Six deviation angles were imposed from 0° to -10°. At each deviation angle, the boundary layers were traversed at 96% chord and the wake at 140% chord (using the cobra probe). Static pressure measurements were taken over the whole plate including the trailing edge.

Due to the definition of positive pitchwise direction, deviation as defined in this paper has the reverse sign of the definition in a turbine geometry.

Plate Pressure Distribution

The plate loading at deviation angles of 0° and -10° is presented in Fig. 9. The imposition of flow deviation has increased the loading over the plate, and has also altered the incidence at the leading edge. To explain this, one must consider the effect of altering the exit panels shown in Fig. 1. The change in streamwise curvature induced in the plate exit plane has the effect of raising the pressure on the pressure side and reducing it on the suction side of the plate. As the freestream stagnation pressure is constant, this alters the velocities and hence (as the flow areas are unchanged) the distribution of mass flow either side of the plate. Hence an increase in the magnitude of deviation on the model corresponds to an increase in the loading on a real turbine blade. This effect is peculiar to the experimental arrangement and is not found in a real turbine cascade.
Boundary Layer Characteristics

The integral parameters of both pressure surface and suction surface boundary layers are presented in Table 3. The results show that the suction surface boundary layer becomes thicker, and the pressure surface boundary layer thinner, as the magnitude of the deviation is increased. This is a result of the increase in magnitude of the pressure gradients on either side of the plate. In addition, the change in mass flow distribution around the plate alters the incidence onto the leading edge. As deviation becomes more negative, the stagnation point moves round the leading edge onto the pressure side. At deviation angles of -6° and less the separation bubble on the pressure surface is eliminated. The pressure surface boundary layer is no longer tripped by the bubble, and remains laminar up to the trailing edge.

Table 3 Boundary Layer Parameters at 96% chord

<table>
<thead>
<tr>
<th>Deviation /deg</th>
<th>Pressure Surface</th>
<th>Suction Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\delta_p$</td>
<td>$\delta_s$</td>
</tr>
<tr>
<td>0</td>
<td>0.039</td>
<td>1.52</td>
</tr>
<tr>
<td>-2</td>
<td>0.038</td>
<td>1.61</td>
</tr>
<tr>
<td>-4</td>
<td>0.037</td>
<td>1.65</td>
</tr>
<tr>
<td>-6</td>
<td>0.030</td>
<td>2.06</td>
</tr>
<tr>
<td>-8</td>
<td>0.026</td>
<td>2.02</td>
</tr>
<tr>
<td>-10</td>
<td>0.025</td>
<td>2.08</td>
</tr>
</tbody>
</table>

Stagnation Pressure Loss

The variation of loss coefficient with deviation is presented in Fig 10. The effect on the boundary layers mentioned above can be seen, both in the net increase in boundary layer loss and in the step reduction in pressure surface boundary layer loss between -6° and -6° deviation. Both profile loss coefficients $Y_{62}$ and $Y_{61}$ are included to illustrate the extent to which mixing has already occurred by 140% chord (20). It is clear that the wake has mixed out more fully at higher deviation angles - the proportion of wake loss still to be created, $(Y_{62} - Y_{61})/(Y_{62} - Y_{61})$, falls from 17% at zero deviation to 9% at -10° deviation. The proportion of the profile loss created in the wake $(Y_{62} - Y_{61})Y_{62}$ falls from 35% to 23.5% over the range of deviation values.

Vortex Shedding

The r.m.s. velocity induced by the vortex street was measured in a section through the wake using a hot-wire aligned parallel to the
trailing edge. A chordwise position of 112% (6t) was chosen, to ensure that the vortex street was fully formed in all cases but had not decayed significantly. The signal was filtered to pass frequencies between 100Hz and 300Hz to remove the bulk of the turbulent fluctuations, and processed to give a value for the r.m.s. velocity. At each deviation angle the maximum r.m.s. velocity occurred to the pressure side of the centreline.

Figure 11 shows the correlation between the proportional wake loss and the vortex shedding intensity, defined as the maximum r.m.s. velocity divided by the freestream velocity. This graph illustrates the connection between vortex shedding and loss creation in the wake.

Discussion

The above results show that an increase in the magnitude of deviation is associated with a weakening of the vortex street and a corresponding reduction in wake loss. Part of the explanation arises from the thickening of the suction surface boundary layer, which in the previous section was shown to inhibit the vortex street partially. However, this does not explain the results entirely: the loss reduction is greater in the present section but the change in boundary layer thickness is less. It is possible that the ratio of the suction- to pressure surface boundary layer thicknesses is a more significant parameter. Even so this cannot account fully for the loss reduction, as the ratio of displacement thicknesses is about the same at -10° deviation as in Test 5 in the previous section. Another possible explanation is that the more laminar state of the pressure surface boundary layer reduces the dissipation in the wake.

Another factor which might play a part in reducing wake loss is the effect of the pitchwise gradients of freestream pressure and velocity, which in the current arrangement are reduced with increased deviation magnitude. Although this is an irrotational effect and does not contribute directly to any reduction in loss, it is possible that the change in the velocities at the wake edges affects the mixing process.

Increasing the loading on the plate by altering the exit deviation seems to reduce the loss produced in the wake. Between deviation angles of 0° and -10°, the profile loss was increased by 5% (due to the thicker suction surface boundary layer) and the loading by 30%. If these results were applied to a turbine scenario, where greater loading per blade equals fewer blades, this corresponds to a net reduction in profile loss of 25%. Such a benefit may not be fully realised, as the effects of blade surface curvature may increase the boundary layer loss more than in the current model. Furthermore, in a real turbine environment, increased loading is usually accompanied by increased pitchwise gradients in the trailing edge plane. As the reverse is true in the current situation, the benefit will be less significant if the pitchwise gradients in the trailing edge plane have an effect on the mixing loss.

CONCLUSIONS

1) The loss produced in the wake of a turbine blade is typically one-third of the total profile loss. Of this, the majority seems to be created within 10 trailing edge thicknesses of the trailing edge.

2) Vortex shedding is inhibited by increasing the ratio of the suction surface boundary layer thickness to the trailing edge thickness. A weaker street produces proportionally less loss in the wake, and the rate of loss creation is less rapid in the near-wake. This conclusion may not apply if the boundary layers separate.

3) The wake loss is significantly reduced by deviation of the exit flowfield. A change in boundary layer characteristics is thought to be partially responsible. It is surmised that the remainder is due to the effect of the freestream velocity on the wake mixing process, although further research is needed to determine if this is the case.

REFERENCES