High Lift and Aft Loaded Profiles for Low Pressure Turbines

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ABSTRACT

This paper shows how it is possible to reduce the number of blades in LP turbines by approximately 15% relative to the first generation of high lift blading employed in the very latest engines. This is achieved through an understanding of the behaviour of the boundary layers on high lift and ultra high lift profiles subjected to incoming wakes.

Initial development of the new profiles was carried out by attaching a flap to the trailing edge of one blade in a linear cascade. The test facility allows for the simulation of upstream wakes by using a moving bar system. Hot wire measurements were made to obtain boundary layer losses and surface mounted hot films were used to observe the changes in boundary layer state. Measurements were taken at a Reynolds number between 100,000 and 210,000.

The effect of increased lift above the datum profile was investigated first with steady and then with unsteady inflow (i.e. with wakes present). For the same profile, the losses generated with wakes present were below those generated by the profile with no wakes present. The boundary layer behaviour on these very high lift pressure distributions suggested that aft loading the profiles would further reduce the profile loss.

Finally, two very highly loaded and aft loaded LP turbine profile were designed and then tested in cascade. The new profiles produced losses only slightly higher than those for the datum profile with unsteady inflow, but generated 15% greater lift.

NOMENCLATURE

\[ C_p \] Pressure coefficient = \[ \sqrt{(P_{in} - p)/(P_{in} - P_2)} \]

\[ C_d \] Drag coefficient

\[ C \] Chord

\[ D \] Bar diameter

\[ f \] Wake passing frequency

\[ f \] Reduced frequency \( fC/V \)

\[ p \] Pressure on surface

\[ Y_p \] Total pressure loss

\[ Y_{rel} \] Relative suction side loss

\[ p_2 \] Stagnation pressure at inlet

\[ p_t \] Pressure on surface at trailing edge

\[ S \] Pitch, or maximum surface length

\[ s \] Surface length

\[ \nu \] Kinematic viscosity

\[ V \] Isentropic velocity on surface

\[ V_2 \] Isentropic velocity at 96% s

\[ \alpha_{1,2} \] Inlet and outlet flow angle respectively

\[ \beta \] Wake relative flow angle

\[ \tau \] Wall shear stress at the wall

\[ \theta \] Boundary layer momentum thickness

\[ \rho \] Density

\[ \infty \] Local free stream

\[ Datum \] Value from the datum profile

\[ le \] leading edge

\[ te \] trailing edge

\[ x \] axial

INTRODUCTION

The fan of a high bypass ratio turbofan engine produces up to 80% of the total thrust of the engine. It is the low-pressure turbine that drives the fan, and on some engines, the LP turbine drives a number of compressor stages. The efficiency of the LP turbine has a large effect on the specific fuel consumption of an engine, where typically, a 1% increase in LP turbine efficiency gives rise to 0.7 - 0.9% increase in engine efficiency (Wisler, 1998). In over 50 years of extensive research, the efficiency of the LP turbine has risen just 10 percentage points. The development of the gas turbine as a whole and the LP turbine in particular has therefore reached a stage...
where rises in efficiency are increasingly hard to obtain. Manufacturers are therefore looking at other ways to make their products more competitive.

The initial cost of the engine, its weight, fuel consumption, maintenance and servicing costs all contribute to the total cost of ownership. However, an engine’s weight has a bearing on both the manufacturing costs and fuel consumption. If one can reduce the number of components in an engine, then any aeroplane it powers will be able to carry increased cargo for the same fuel load. Reducing the number of components may also increase reliability, since there are fewer components to fail. The heaviest single component is often the LP turbine. In some engines, it can comprise one third of the total weight. The LP turbine is therefore a prime component for reducing total engine weight.

Profile loss in the boundary layers is the main loss generating mechanism caused by the blades in an LP turbine. This is because the high aspect ratios (typically 5:1) of these blades means that there is relatively little surface covered by secondary flow. A well-behaved pressure side flow will also contribute little to the total losses generated. Curtis et al (1996) reports a loss breakdown for a conventional LP turbine blade. This indicated that up to 60% of the losses were generated by the suction surface boundary layers.

The weight and manufacturing cost of the LP turbine can be reduced by reducing the number of blades. It is to this end that the research described in this paper is aimed. In reducing the number of blades in a stage, each blade must carry a greater aerodynamic load. This leads to greater deceleration over the rear of the suction surface. Conventional (i.e. steady) wisdom dictates that this would increase the risk that a separated laminar boundary layer might not reattach. An open separation at the trailing edge would result in a unacceptably high profile loss.

Hourmouziadis (1989) introduced the concept of controlled diffusion blading that was designed to keep the suction surface boundary layer attached. Boundary layer separation was allowed, but it was designed to occur soon after peak suction. Because peak suction occurred at mid chord, the separated boundary layer could reattach before the trailing edge. These profiles were designed to give low loss coefficients and only steady flow effects were considered.

Schulte and Hodson (1996) investigated the effects of moving bars and their wakes on the losses generated by an LP turbine cascade. In some cases and at some Reynolds numbers, the effect of incident wakes resulted in the cascade producing lower losses than it did with steady flow. As wakes shed from upstream blade rows travel over the downstream blade rows, they disturb the boundary layers. As the boundary layers become more receptive to disturbances, the wakes eventually cause the formation of turbulent spots through the mechanism of bypass transition. These spots travel downstream in a characteristic manner (Schubauer and Klebanoff, 1955). Behind the spot is a calm region of flow that has a full velocity profile. This profile is very stable and does not separate in adverse pressure gradients as easily as a laminar profile. Schulte and Hodson (1996) argued that it was this ability to withstand adverse pressure gradients that allowed the spots to keep a flow from separating. It was also shown that this interaction was responsible for the loss reductions.

The main objective of this research was to improve the understanding of the suction side boundary layers under the influence of wakes with the aim of increasing the lift of the profiles. The datum profile to which all other measurements are compared to is the high lift profile H as described by Curtis et al (1996).

**EXPERIMENTAL DETAILS**

Figure 1 shows a schematic diagram of the experimental rig. This consists of the cascade of seven blades and a moving bar mechanism that allows bars to be traversed upstream of the leading edge of the cascade. The bars are fitted to belts and carried on wheels that are driven by a variable speed DC motor. The speed of the bars was set to give the required flow coefficient $(\psi = \frac{V}{U_{in}})$). The bar to cascade pitch ratio was set to the same value (1.5) as that of an equivalent LP turbine. The traverse mechanism allows measurements to be performed within the blade passage.

![Figure 1 Schematic of moving bar rig and cascade.](image)

The inlet stagnation temperature was measured using a thermocouple that was placed within the inlet plenum. A Pitot probe placed downstream of the moving bars provided the reference cascade inlet stagnation pressure.

The bar diameter was chosen so that the wakes they produced gave rise to the same losses as those generated by a typical upstream LP turbine blade row. It can be shown that the approximate total pressure loss coefficient for the bars is given by the following expression

$$ Y_p = \frac{C_D D}{S_{in} \cos \beta} \quad (1) $$

where $C_D$ is the drag coefficient of the bar at the bar Reynolds number used in the tests and $D$ is the bar diameter. Full details of the simulation capabilities of the moving bar rig can be found in Schulte (1995).

The moving bars also accurately simulated the inlet turbulence intensity of an upstream blade row. Measurements showed that the bars produced a variation in inlet turbulence comparable to that at the inlet to a 1.5 stage large-scale turbine with the same profiles (Benignebl et al, 1995). The bars produced a peak turbulence measured at inlet to the cascade of 13%, with a velocity defect of approximately 10% of the undisturbed freestream value. The reduced frequency of the bar and cascade system was set to the value (0.78) where minimum losses were measured for the datum profile, see Schulte and Hodson (1996).

In one series of experiments, a number of pressure distributions were created by placing a flap below the one instrumented with static pressure tappings (see Figure 2). These were then tested for their performance with steady and unsteady inflow. As the flap is rotated around the trailing edge of the blade to which it is attached, it alters the effective exit area of the blade row above. Obviously, the cascade is no longer periodic, but if it is only the suction side distribution that is of interest this does not matter. Details of the analysis of the data obtained from this flap-modified cascade are given in the next section.

In addition to the flap, a number of inserts were placed into the blade passage as shown in the same figure and these were used to alter the position of peak suction on the blade surface. When the flap was at large angles from the vertical, suction was also applied to the flap surface. This was designed to keep the boundary layer attached to the flap, so that very high loadings could be achieved on the test profile.
In addition, errors of 20% or more arise when hot films were developed by Bellhouse and Schultz (1966) and is now a well-established technique. It is possible to calibrate hot films, but this is a difficult and time-consuming process (see Hodson, 1985) has been applied to the data. The effect due to changes in ambient temperature upon the hot wire calibration were accounted for with the correction of Bearman (1971).

The hot wire traverses were made near the blade trailing edge, at 96% surface length and in a direction normal to the surface. Up to 30 positions through the boundary layer for a given blade profile. The use of a single hot wire (at the trailing edge) is perfectly acceptable because any loss data presented is from only turbulent and attached boundary layers. The use of a hot wire within a separation bubble is subject to many errors.

Hot film measurements have also been performed to assess the development of the blade surface boundary layers and relate these finding to the losses generated by the profiles. The measurement of wall shear stress using hot films was developed by Bellhouse and Schultz (1966) and is now a well-established technique. It is possible to calibrate hot films, but this is a difficult and time-consuming process (see Hodson (1983) and Davies and Duffy (1998)). In addition, errors of 20% or more arise when hot films calibrated in a laminar flow are used to measure a turbulent flow. The hot film sensors used on the aft part of the suction surface were likely to see laminar, turbulent and separated flow at different positions of the upstream rotor. Their calibration would therefore be extremely difficult and quite probably impossible.

The hot film and hot wire measurements were carried out at mid-span of the blade. The spacing between each hot film sensor was approximately 3% surface length. Error analysis showed that the total pressure loss error is ±0.15%, the traverse positioning accuracy was ±0.05mm and the momentum thickness repeatability was within 1%.

**Measurement of relative lift and loss**

When the flap is fitted, the cascade is no longer periodic. Therefore, it is not possible to carry out wake traverses to measure profile loss. The measured boundary layer momentum thickness at 96% of the blade is used to calculate the loss due to the suction side boundary layer. Denton (1993) used a control volume analysis to derive an expression for the loss generated by the suction and pressure side boundary layers, trailing edge and mixing out of the flow over a turbine blade. The calculation of loss in the current paper only takes into account the suction side boundary layer losses.

The suction side losses are assumed proportional to the momentum thickness at the trailing edge and inversely proportional to the pitch of the blade. The value of loss relative to the datum profile is given by the expression below

\[ Y_{rel} = \frac{\theta}{\theta_{datum}} \cdot \frac{S_{datum}}{S} \]  \hspace{1cm} (4)

where \( \theta \) is the trailing edge momentum thickness, and \( S \) is the equivalent pitch of the pressure distribution under investigation. Implicit in the above arguments are the assumptions that the shape factor and exit angles remain constant. All the measurements made with wakes present produced an attached turbulent boundary layer at the trailing edge of the blade, resulting in very similar shape factors. When wakes are present, the separation bubble is suppressed and the exit angles are assumed constant.

Increasing the lift of a profile amounts to increasing the pitch of an equivalent cascade, i.e. reducing the number of blades. There are then fewer blades generating losses and this is taken into account in equation 4. The expression given above requires a value of equivalent pitch that would result in the profile for which the losses were measured. The circulation related to the pitch by the following expression

\[ \int V \cdot ds = S \cos \alpha_1 (\tan \alpha_1 - \tan \alpha_2) / \rho V h \]  \hspace{1cm} (5)

The circulation is evaluated from the measured pressure distribution and is used to find the pitch of the equivalent cascade. A constant value of inlet and exit angle was used because the new pressure distributions were for a particular duty. The pressure side pressure distribution from the datum profile (H) was used for all calculations.

Curtis et al (1996) assumed constant values for the losses produced by the pressure side, trailing edge and boundary layer blockage. In the following analysis, rather than assuming that those losses are constant, they have not been included because it is extremely difficult to determine how they change with increasing lift. Including these 'extra' losses will dilute the effects of the loss reduction that occurs on the suction side due to the presence of wakes.

**RESULTS and DISCUSSION: THE DATUM PROFILE**

The suction side pressure distribution of the datum profile (H) is shown in Figure 3. This was measured with steady inflow and at a Reynolds number of 130,000. It is designated profile H, by Curtis et al (1996). However, it should be noted that Curtis et al conducted their investigations at a Reynolds number of 210,000. The profile is typical of those used in some of the newer turbine engines currently in service.
The datum profile (H) exhibits high leading edge loading with a continual acceleration up to peak suction, which occurs at around 53% surface length. The flow then undergoes a large deceleration and consequently (with steady inflow) separates from the blade surface and forms a separation bubble. The bubble undergoes transition at about 95% and the flow reattaches before the trailing edge of the blade.

The effect of Reynolds number changes on the losses produced by the datum profile is shown in Figure 4. The trailing edge momentum thickness is made non-dimensional by the momentum thickness measured with unsteady inflow at a Reynolds number of 130,000.

Subtracting the momentum thickness calculated using equation 6 from the measured value at 96% gives the amount of loss due to the separation, reattachment process and development of the turbulent boundary layer. On the datum profile, the separation bubble is responsible for producing more than 60% of the total boundary layer losses. The development of the very small (less than 2%) amount of turbulent boundary layer after reattachment was ignored in this simple calculation.

Figure 4 shows that there is a large loss reduction at low Reynolds numbers due to the effects of the wakes. As the Reynolds number increases, the loss reduction diminishes to the point where at a value of 2.1x10⁵ there is almost no loss reduction. The reduction in the difference in losses with increased Reynolds number is due to the reduction in the size of the separation bubble. If the size and loss generated by a separation bubble is smaller then so is the possible loss reduction due to the effects of wakes. This is the situation at the higher Reynolds numbers.

The low Reynolds number condition (1.3x10⁵) was selected for the tests presented here since this is the greatest loss reduction occurred. This Reynolds number is also that found in the last stages of the largest turbofan engines such as the Trent series and it is also that found in the first few stages of smaller engines such as the BR700 series. The datum pressure distribution (profile H) shown in Figure 3 and its measured trailing edge momentum thickness was taken as the datum values for non-dimensioning the results presented in this paper.

**HIGHER LIFT PROFILES**

Having described the performance of the datum profile, it is now appropriate to look at the performance of more highly loaded profiles, using the attached flap. One way of increasing the lift further is to decrease the minimum pressure on the suction side. Unfortunately, this increases the deceleration that the flow must go through. To increase the lift on the instrumented blade, the flap was rotated away from the suction surface of that blade. The pressure ratio driving the flow through the passage is that from the inlet to the cascade, to the exit created between the instrumented blade suction surface and flap. When the outlet area increases so does the mass flow through the passage. The exit velocity is approximately constant, as is the throat area so the velocity there must increase resulting in a larger deceleration over the back surface.

Figure 3 shows the effect of increasing the flap angle on the resulting pressure distributions. The geometric position of the throat and therefore the appropriate position of peak suction was kept constant in these tests.

Hot film measurements carried out on these profiles indicated that the location of boundary layer separation remained approximately constant (i.e. within the 3% resolution of the hot film gauges) with steady inflow. The reattachment location of the steady flow separation bubble moved away from the trailing edge of the blade with increased loading. Howell (1999) showed that the surface length of the bubble reduced with increasing lift, but the surface normal height of the bubble increased as did the losses it generated.

![Graph](https://via.placeholder.com/150)

**Table 1** Separation and multi-mode transition locations for a range of profiles taken from hot film measurements and at a Reynolds number of 130,000.

<table>
<thead>
<tr>
<th>Profile</th>
<th>Separation (%s)</th>
<th>Wake Induced Transition (%s)</th>
<th>Separated Flow Transition (%s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>74</td>
<td>77</td>
<td>95</td>
</tr>
<tr>
<td>A</td>
<td>74</td>
<td>77</td>
<td>92</td>
</tr>
<tr>
<td>B</td>
<td>74</td>
<td>77</td>
<td>86</td>
</tr>
<tr>
<td>C</td>
<td>80</td>
<td>83</td>
<td>92</td>
</tr>
<tr>
<td>U1</td>
<td>74</td>
<td>79</td>
<td>84</td>
</tr>
</tbody>
</table>

Table 1 shows a summary of the measurements and analysis of hot film data taken from the above profiles and profile ‘C’ which is discussed later. The location of wake induced transition also remained constant with increases in peak velocity and occurred in all cases just after the separation position. The data in table 1 indicates that the increase in deceleration seems to cause the separation to become more receptive to disturbances and it starts to undergo transition and therefore reattachment earlier. Hot film data confirms this, but is not shown for brevity. Wake induced transition only occurs around the separation position. This detail has also been noted in flows over other high lift turbine blade profiles. For example, Howell (1999) used hot film gauges to measure transition phenomena on a high speed, full-scale rig of the BRR 715 and 710 LP turbines. These measurements showed that wake induced transition does not occur until around the region where the boundary layer separates. The values of Reₘₐₓ is approximately 250 just before separation¹ on both the BMW Rolls-Royce high speed profiles and the profiles presented in this paper. The details of the pressure distribution will also effect Reₘₐₓ. However, calculation of the momentum thickness showed that there was very little variation between profiles. In all cases, the values approached a value of approximately 250 just before separation. Profiles A and H, for example, give rise to a difference in momentum thickness of only 5%. They are however radically different pressure distributions. This illustrates that details in the pressure distribution are not

¹ This location is the same for steady flow and where transition occurs between wake passings.
² Measured 5%S before the separation location.
particularly important in determining momentum thickness just before separation.

At a Reynolds number of 130,000 the results suggest that a wake produced by a well behaved LP turbine blade (in this case producing an inlet turbulence intensity of 14%, Banieghbal et al 1995) does not cause transition before separation. This is because there is a continual acceleration up to peak suction, keeping the boundary layer stable. From a practical standpoint, this means that sophisticated transition onset models are not required. Once the position of separation is known, this essentially fixes the wake induced transition onset location at design conditions. Larger bars producing stronger wakes do however cause transition onset before separation as noted by Schulte (1995). However, these wakes cannot be considered typical of an LP turbine operating at design conditions.

At higher Reynolds numbers, the flow is more receptive to disturbances and one would expect wake-induced transition to occur earlier. However, hot film measurements on the datum profile at a Reynolds number of 210,000 indicates that wake transition still occurred at approximately the separation location.

Figure 5 Variation in loss with increased lift, with and without wakes at a Reynolds number of 130,000.

Figure 5 shows the relative suction side boundary layer loss ratio against lift ratio. The losses are made non-dimensional by the loss of the datum profile (H) with unsteady inflow. The lift ratio is also made non-dimensional by the lift value of the datum profile with unsteady inflow. As expected, when the lift is increased above that of the datum profile, the suction surface loss increases. This loss increase under steady flow conditions is partly due to the increased turbulent boundary layer that is allowed to develop because of the wakes alone. Removing some turbulent boundary layer (by pushing the position of peak suction/velocity (and therefore separation) towards the trailing edge would reduce the profile loss. This was carried out in by placing inserts into the blade passage as shown in Figure 2. It should be noted that in all of the experiments presented in this section, the reduced frequency was kept constant.

AFT LOADED PROFILES

Results have shown that the effect of upstream wakes on the profile loss of a downstream suction surface boundary layer is beneficial, especially at high loadings and low Reynolds numbers. At very high loading, hot film measurements indicated that there was a large amount of surface covered in transitional and turbulent flow after boundary layer reattachment. Reducing this area of turbulent flow will result in a reduction in profile loss. An ST-diagram can illustrate the unsteady transition process by placing variations of boundary layer state in time and space on a single diagram, see Figure 6. The y-axis shows multiples of wake passings and the x-axis shows the surface distance. Transitional flow caused by wakes are marked W, turbulent flow caused by separated flow transition is marked T and calmed flow is marked C. The diagram shows two cases of wake passings at different reduced frequencies. Figure 6a shows a reduced frequency similar to that for the profile shown here where separated flow transition occurs between wake passings. The region marked B, between wakes one and two, shows turbulent flow due to the separation bubble. At this, lower reduced frequency, the flow at the trailing edge is turbulent because of the wakes, then calmed and then turbulent again due to the separation bubble transition. However, if the time between wake passings was sufficiently short (i.e. a high reduced frequency), then the separation bubble may never have time to re-establish itself. This is the case in Figure 6b. In this case, the flow at the trailing edge is fully turbulent because of the wakes alone. Removing some turbulent boundary layer (by pushing the position of peak suction/velocity (and therefore separation) towards the trailing edge would reduce the profile loss. This was carried out in by placing inserts into the blade passage as shown in Figure 2. It should be noted that in all of the experiments presented in this section, the reduced frequency was kept constant.

The datum pressure distribution resulted in a position of peak suction at about 53% and boundary layer separation at 74%. In the following investigations, the position of peak suction was moved to 60, 65 and 68%. For example, the profile with peak suction at 65% resulted in separation at 80%, a rearwards shift of 6%. Steady flow hot wire and hot film measurements of the boundary layer at 96% showed that sometimes the separation bubble did not reattach before the trailing edge of the blade on some pressure distributions. Open separations result in an unacceptable large profile loss. However, when the same pressure distribution was subjected to incoming wakes, it was found that the boundary layer at 96% was always attached, no matter what the loading, or position of peak suction. The loss measurements (i.e. of momentum thickness) at 96% with unsteady inflow with a hot wire are therefore valid.
Due to the construction of the experimental rig, it was not possible to conduct a well-ordered parametric investigation. This is because accurate control over the details of the pressure distributions was difficult to achieve. An ideal pressure distribution would look like the one for the datum blade but with a higher loading with peak suction nearer the trailing edge. Some pressure distributions produced large decelerations, but little loading over the forward part of the blade. These sorts of pressure distributions resulted in only a small or no increase in lift over the datum profile. Therefore, a wide spread of measurements for various pressure distributions was obtained, but some of which turned out not to be satisfactory.

Figure 7 shows the pressure distribution of the aft loaded profile ‘C’ and also the datum profile measured with wakes present. The results show that the separation bubble, if it exists, has a small effect.

Figure 8 Variation of losses with position of peak suction.

Figure 8 shows the variation in relative suction side loss vs. the position of peak suction for a range of lift coefficients. The losses are made non-dimensional by the loss of the datum profile with unsteady inflow. Unless otherwise stated all measurements were made with wakes present. Figure 8 shows an obvious trend for the pressure losses to reduce when the position of peak suction is moved aft. The reduction in loss can be attributed to a reduction in surface covered in turbulent boundary layer and also to the reduction in turbulent boundary layer due to the wakes, as illustrated in Figure 6. The scatter of the data for each peak suction position is due to the different loadings that the pressure distributions produced. Profile C produced 15% more lift than the datum profile and a similar level of loss. Table 1 shows details of the transition mechanisms for this profile. The value of Re just before separation is around 250 which is similar to other profiles such as those in the BR700 series of LP turbines as measured by Howell (1999).

Hot film measurements from profile C also showed that wake induced transition occurred just after separation, see position ‘S’ in Figure 9. Figure 9 is an ST-diagram of the non-dimensional ensemble mean shear stress on profiles C and H. The locations of the hot film sensors are indicated by black dots at the top of the figure. The shear stress is made non-dimensional by the maximum value of shear stress measured by each sensor, i.e. \( \frac{\tau(s,t)}{\tau_{\text{rms}}(s)} \) is plotted, where \( t \) is time. This serves to enhance the periodic fluctuations in shear stress, but at the expense of the overall levels of shear stress. In fact, the levels of shear stress at 60% s are much less than those at 96% s.

Figure 9 ST diagram of non-dimensional ensemble mean quasi shear stress data from profiles H and C at a Reynolds Number of 130,000, and flow coefficient of 0.7.

Hot film data from profiles C and H exhibit the same basic structure. Wake induced transition starts in the regions marked and this coincides with the position of flow separation, marked ‘S’. The regions of transitional flow are classical in that they are wedge shaped. The wedge is caused by the difference in leading and trailing edge propagation rates of the turbulent spots that are created by the wakes. The regions marked ‘L’ have a lower shear stress level than the wake induced transition regions downstream. These are caused by the wake’s velocity defect on the laminar boundary layer and are not caused by transitional flow.

Figure 10 Relative suction side boundary layer losses for aft loaded profiles measured with and without wakes present. Re = 130,000
Figure 10 shows relative suction surface boundary layer loss against relative lift for distributions with peak suction 65%, for cases with and without wakes. Again, the losses are made non-dimensional by the loss of the datum profile (H) with unsteady inflow. The lift ratio is also made non-dimensional by the lift value of the datum profile (H) with unsteady inflow. This figure does show that aft loading turbine blades are only possible when wakes are present to control the losses generated in the reattaching part of the separation bubble.

THE ULTRA HIGH LIFT PROFILES

Having established the boundary layer features that are present on ultra highly loaded LP turbine blades with incoming wakes, two new ultra high lift profiles were designed and tested in cascade.

Figure 11 shows the new ultra high lift velocity distributions, U1 and U2 and the datum profile H. All distributions are measured with unsteady inflow and velocities are made non-dimensional by using the cascade exit velocity, \( Re = 130,000 \).

Figure 11 shows the new ultra high lift velocity distributions, U1 and U2 and the datum profile (H) measured with unsteady inflow. The design brief for these profiles was to achieve an increase in lift of approximately 15% compared to the datum profile H. The inlet and exit angles were the same as the datum cascade and the design Reynolds number was chosen to be 130,000. The best lift - loss pressure distributions, presented earlier, seem to be those that produced peak suction at 65% and separation at around 80%. The position for laminar separation was therefore designed to occur at approximately 80%, and the value of \( Re_b \) was designed to be approximately 250. This ensures that wake induced transition would be initiated in this region. The presence of the turbulent spots, calm regions and wake turbulence then controls the separation bubble growth and loss generation.

These velocity distributions in Figure 11 were made non-dimensional by the cascade exit velocity. This is the correct way of presenting cascade data, whereas for the tests using the attached flap the static pressure at 96% was used. Unfortunately, figure 11 shows that increasing the lift tends to depress the trailing edge velocity. This occurs because as the lift increases the amount of uncovered turning on the rear of the suction surface also increases. For example, the geometric throat is at approximately 45% for the profile U1 and there is approximately 10° of inviscid deviation. The uncovered turning is used to maintain the high suction side velocities, downstream of the geometric throat. This large amount of uncovered turning suppresses the velocity at the trailing edge of the aerofoil. This occurs because, for a given mean exit angle, the potential field of each profile increases in strength as the lift increases. Therefore, there is a greater re-distribution of the streamlines once the flow passes beyond the trailing edge plane. This means that the velocity at the trailing edge is lower than that at the cascade exit plane.

The deceleration between peak suction (or peak velocity) and the exit plane is what would be expected on a profile without a convex rear suction surface. On these ultra-high lift profiles, the flow must decelerate to a much lower value at the trailing edge. An unfortunate consequence of the above is that as the lift is increased, the amount of suction surface deceleration increases far more than would be expected if only the peak velocity and cascade exit velocity were considered. Ultimately, this will limit the amount of lift that is practicably possible.

The two ultra-high lift profiles (U1 and U2) both generate the same lift and so must have the same total circulation. However, the ultra-high lift profiles are of two different designs with different circulation distributions. Profile U1 resulted in a rather flat-topped velocity distribution, Hot film measurements showed separation was detected at approximately 75% and wake induced transition occurred at 80%. The flat top pressure distribution allowed the boundary layer to grow more quickly than it would if the flow was still accelerating. Unfortunately, this profile has a similar separation location to the datum profile and this, combined with the flat top pressure distribution and increased diffusion, is likely to lead to higher losses.

To avoid the flat top pressure distribution, profile U2 has an increased peak velocity to give the continual acceleration and allow proper aft loading of the velocity distribution. However, as discussed above, this lead to an even larger back surface diffusion than for profile U1 and resulted in much higher losses than expected.

Figure 12 shows the variation of relative total pressure losses from the ultra high lift profiles (and for the datum profile) for a number of reduced frequencies. All total pressure loss values are made non-dimensional by the loss for the datum profile (H) at a Reynolds number of 130,000 with wakes present (reduced frequency of 0.78).

The losses generated by profile U2 are considerably higher than those for the other profiles are even when wakes are present. To illustrate this, the losses produced with steady inflow on profile U2 reached seven times the datum profile losses with unsteady inflow. The losses of profile U2 were high, but this was due to the elevated level of deceleration caused by the suppressed trailing edge velocity. Profile U1 produces losses that are also very high with steady inflow. However, when wakes are present, the losses reach a level that is more comparable to the datum profile. It should of course be remembered that both profiles U1 and U2 have 15% more lift than profile H. As the Reynolds numbers are increased, the performance of the ultra-high lift profiles improves dramatically.
This is because the separation bubble losses are being reduced. By a Reynolds number of 170,000, the losses are roughly the same as the datum profile.

Further discussion

The new ultra high-lift profiles produced greater losses than those for the datum profile at the design Reynolds number, but resulted in a decrease in the number of blades by 15%. Laminar separation occurred on profile U1 at approximately the same surface position as for the datum profile. Hot film measurements indicated the presence of turbulent boundary layer near the trailing edge. The separation location was moved further aft for profile U2, but required an increase in peak velocity to achieve this. The increased deceleration caused by this resulted in higher losses than those for the datum profile.

At very low Reynolds numbers, the greater the reduced frequency the lower the losses. Howell (1999) and Arndt (1991) showed that stator 3 of a three stage LP turbine had wake induced turbulent regions on the suction surface appearing at twice the frequency of the wake passing of rotor 2. This effectively results in a doubling of the reduced frequency to which stator 3 is subjected. This can be considered beneficial for the current ultra high-lift profiles. This effect should reduce losses if this type of profile was used in an imbedded stage rather than just subjected to the wakes from a single upstream rotor. Higher Reynolds numbers occur in the first stages of the LP turbine while lower Reynolds numbers occur in later stages. This is fortuitous as high reduced frequencies (caused by multistage interactions) occur in later stages in the LP turbine where the larger separations (due to lower Reynolds numbers) are likely to be better controlled. In the first few stages, there are less blade row interactions, but as Figure 12 showed one does not desire reduced frequency doubling as this increases losses.

The measurements presented in this paper were carried out with a freestream turbulence level of 0.5%. This level is lower than that in the engine environment and can be considered a worse case scenario. The size (and losses) of separation bubbles reduce when subjected to elevated levels of freestream turbulence. With a higher turbulence level, the losses are likely to be further reduced at low Reynolds numbers. Using the ultra-high lift profiles in an engine environment is therefore likely to the losses further.

CONCLUSIONS

In low Reynolds number flows (typically 130,000), the presence of wakes on the suction side boundary layer on a highly loaded LP turbine blade has a profound effect on the losses generated.

For a fixed position of peak suction with increased loading, steady flow reattachment of the boundary layer moved further from the trailing edge. This resulted in a large amount of blade surface covered in turbulent boundary layer. Aft loading the pressure distributions decreased the amount of turbulent boundary flow present and so reduced the losses generated. Aft loaded profiles are only viable when they are used with incoming wakes.

Two new highly loaded LP turbine profiles were designed using the data presented in this paper. With steady inflow the profiles, as expected, performed poorly. When subjected to unsteady inflow the profile lost reduced dramatically. The profiles generate 15% more lift than the datum. The amount of suction surface deceleration was greater than anticipated due to the large back surface curvature on these profiles used to aft load the profiles. This curvature suppressed the trailing edge velocity, increasing the deceleration required by the flow. This effect limits how high the lift on such profile may be pushed in the future because of the effect on the losses. It may well be that the limit has been reached with these profiles and even the effect of wakes cannot control the large losses generated by the separation bubble.

Controlled diffusion blading takes no account of the effects of upstream wakes. By understanding the unsteady effects of wakes and using them carefully, the current limits placed on the deceleration level, location of peak suction and separation are reduced. Profiles that generate acceptable losses but increased lift will therefore be possible by including the new design ideas.

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