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Boundary Layer Development in the BR710 and BR715 LP Turbines -

The Implementation of High Lift and Ultra High Lift Concepts

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ABSTRACT

This paper describes a detailed study into the unsteady boundary layer behaviour in two high lift and one ultra high lift Rolls-Royce Deutschland LP turbines. The objectives of the paper are to show that high lift and ultra high-lift concepts have been successfully incorporated into the design of these new LP turbine profiles.

Measurements from surface mounted hot film sensors were made in full size, cold flow test rigs at the altitude test facility at Stuttgart University. The LP turbine blade profiles are thought to be state of the art in terms of their lift and design philosophy. The two high lift profiles represent slightly different styles of velocity distribution. The first high-lift profile comes from a two stage LP turbine (the BR710 cold-flow, high-lift demonstrator rig). The second high-lift profile tested is from a three-stage machine (the BR715 LPT rig). The ultra-high lift profile measurements come from a redesign of the BR715 LP turbine: this is designated the BR715UHL LP turbine. This ultra high-lift profile represents a 12% reduction in blade numbers compared to the original BR715 turbine.

The results from NGV2 on all of the turbines show "classical" unsteady boundary layer behaviour. The measurements from NGV3 (of both the BR715 and BR715UHL turbines) are more complicated, but can still be broken down into classical regions of wake-induced transition, natural transition and calming. The wakes from both upstream rotors and NGVs interact in a complicated manner, affecting the suction surface boundary layer of NGV3. This has important implications for the prediction of the flows on blade rows in multistage environments.

NOMENCLATURE

τ_w	Quasi wall shear stress
τ'_w	RMS of signal
$\tilde{\tau}_w$	Non-dimensional ensemble mean quasi wall shear stress
$\tilde{\tau}'_w$	Non-dimensional ensemble mean RMS
s	Surface length
t	Time
δ^*	Boundary layer displacement thickness
θ	Boundary layer momentum thickness
∞	Local free stream

INTRODUCTION

Since the fan of a high bypass ratio turbo fan engine produces up to 80% of the total thrust of an engine it is vital that the low pressure turbine that drives it is efficient. A 1% increase in LP turbine efficiency gives rise to a 0.7-0.9% increase in engine efficiency see Wisler [1]. In over 50 years of extensive research the efficiency of the LP turbine has risen just 10 percentage points to today's efficiency levels of over 90%. 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 for other ways to make their products more competitive.

Engine weight reductions provide financial benefits to both the airlines and to the engine manufacturers. The LP turbine can be up to one third of the total engine weight. A way of decreasing its weight and manufacturing costs is to reduce the number of blades. In doing this for a given stage loading, each blade must carry a greater aerodynamic load. The main loss generation mechanism in the LP turbine is that due to profile loss in the boundary layers. When increasing the lift of a profile it is therefore vital to understand the boundary layer development. The data presented in this paper validates the design concepts used in producing these high lift profiles.

This paper is organised so that it clearlty shows the development of both the understanding of wake-boundary layer interactions and the development of high and then ultra high lift LP turbine blades. After an introduction to the subject, the experimental methods are then presented. Hot film results are then presented from LP turbines that represent conventional, high lift and finally ultra high lift designs. Each turbine design represents a step in the evolution of our understanding of the aerodymanics of these turbines and the resutls show the increasing complexity of the flows.

High Lift Concepts – a brief overview

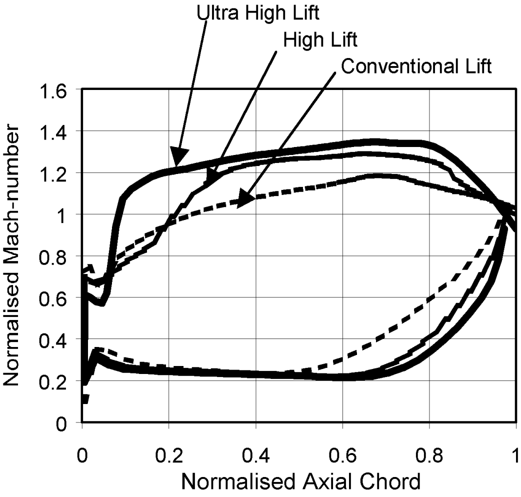

Figure 1 Comparison of predicted Conventional Lift, High Lift & Ultra High Lift Mach Number distributions (normalised). After Haselbach et al [13].

The Mach number distribution for conventional lift blading in Figure 1 has a large and continual acceleration over the leading part of the suction surface and up to the peak Mach number. Although not shown in these inviscid predictions, soon after the peak Mach number, the flow separates under the adverse pressure gradients. Up to the peak Mach number, the acceleration is high enough and the momentum thickness Reynolds number low enough to keep the boundary layers laminar, despite the effects of periodic wake turbulence. A boundary layer is unstable when it is being decelerated. Therefore, the turbulence from the periodic passing of wakes is likely to cause transition from laminar to turbulent flow. However, as is often the case (see Howell et al [2]) this transition does not occur until very near the position where the laminar flow starts to detach from the blade surface. The exact reason for this is not fully understood, but it could simply be that a separated shear layer (or a boundary layer near separation) is highly unstable. It therefore transitions easily when the wake turbulence is above it.

Curtis et al [3] showed, through a loss-lift parametric study involving a large number of profiles, that it was possible, with steady flow, to increase the lift of a datum profile by approximately 20% without an increase in profile loss. Those studies were carried out at a higher Reynolds number than those presented in this paper. The increased lift profile (a so called high lift profile) resulted in a Zweifel coefficient of 1.05. Some of these profiles produced separation bubbles on the rear of the suction surface. The results suggested an optimum profile would be something similar to that shown in Figure 1.

Wakes shed from upstream blade rows travel over downstream blades disturb their boundary layers, see Hodson [4] and Ladwig and Fottner [5]. As a boundary layer becomes more receptive to disturbances, the high turbulence in the wakes eventually causes the formation of turbulent spots through the mechanism of bypass transition. Schauber and Klebanoff [6] showed that these spots travel down stream in a characteristic manner. An ST diagram is a contour plot of, for example shear stress, with time on the 'y' axis and surface distance on the 'x' axis, see Figure 2. The different celerities of the leading and trailing edges of the turbulent spots mean that the regions of high shear seen in ST diagrams diverge in time. This is because the leading and trailing edge velocities of turbulent spots are reported to travel at approximately 90% and 50% of the local free stream velocity for zero pressure gradient flow. Behind the spot is a calmed region of flow that has a full velocity profile, which is shown in Figure 2 as region 'C'. This profile (which is almost linear out to the freestream, Cumpsty et al [7]) is very stable to disturbances and will not so easily separate in an adverse pressure gradient, as a laminar profile would. The value of the trailing edge velocity is highly dependent on the local pressure gradient, but the leading edge velocity is almost unaffected by it. The ends of calmed regions that trail turbulent spots are variously reported to travel at approximately 30% of the local free stream velocity, see Gostelow et al [8]. The effect of variable pressure gradient on the velocity of the calmed region has not been documented.

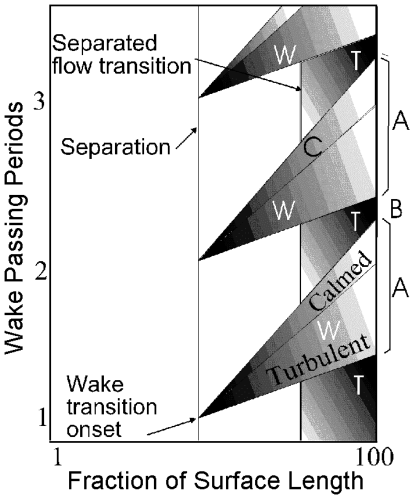

Figure 2 A schematic diagram of wake induced transition and separated flow transition.

Schulte [9] showed the details of how the losses were controlled at a Reynolds numbers of 130,000. He showed that it was the interaction of the calmed regions of turbulent spots (formed by wake passing) that suppressed the separation bubble. This separation bubble suppression is the reason for the control of the losses on the high lift turbine profiles. Howell [10] and Howell et al [2] showed that this understanding could be taken further. Still higher lift blades were investigated in cascade tests – the so called ultra high lift profiles.

The control of the separation bubbles and their losses is dependant on wake induced transition occurring around the separation location. Wake induced transition usually starts at the position where flow separation would occur with steady inflow. This is true in all the cases presented in this paper. The Reynolds number tested here ranged from 60,000 to 120,000. The low speed measurements taken at the Whittle Laboratory on a variety of profiles and at a variety of Reynolds numbers above 130,000 also indicate the same onset location of wake-induced transition. In many of the low speed tests carried out, the Reynolds number based on momentum thickness was approximately 250 just before separation. This obviously changes slightly depending on the pressure distribution. However, for the ultra high lift profiles (the BR715UHL) part of the design specification was actually to achieve a momentum thickness Reynolds number of at least 250, by the position of separation. This helped to guarantee that wake induced transition occurs at the separation location. This in turn keeps the performance of Ultra High Lift profile at similar levels to previous generations of high lift or low lift designs.

From these Whittle Laboratory tests, Rolls-Royce Deutschland designed the profiles employed on the BR715UHL LP turbine. To control losses the profiles were aft loaded. Wakes and their effects were used to control the losses generated by the separation bubbles present in these designs. Howell [10] also showed that it is also the wake turbulence and not just the effect of the calmed region that helps to suppress the losses generated by the bubbles on ultra high lift profiles.

Cobley *et al* [11] describes the many parts of the design process leading to the development of the LP turbines in the BR700 series of engines. They also describe some of the design methodologies used to develop the high lift profiles. Harvey *et al* [12] showed that the efficiency of these LP turbines is approximately the same as previous generations. In particular the BR715 actually achieved an efficiency above previous generation LP turbines as well as 20% reduction in blade numbers. Figure 3 (taken from Haselbach et al [13]) shows the increased lift obtained for the three profiles shown here as compared to current Rolls-Royce designs. These levels of performance were obtained without a loss penalty.

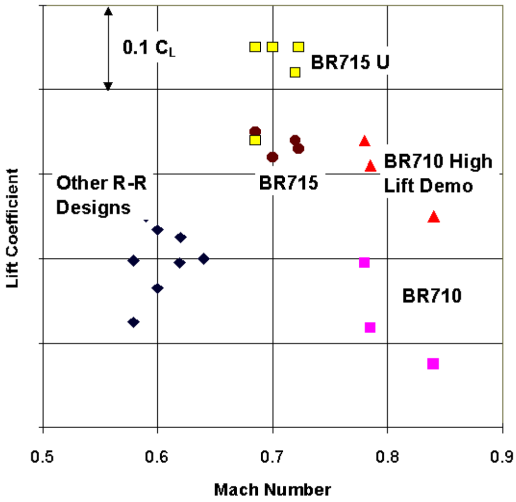

Figure 3 Lift coefficient vs. Mach number for a variety of blade profiles, including the high lift profiles of the BR715 and BR710 demonstrator. The BR715UHL turbine achieves even high lift coefficients. After Haselbach et al (2001).

The BR715UHL LP turbine is the most highly loaded turbine ever tested by Rolls Royce Deutschland – formally BMW Rolls Royce. No unsteady design tools were available at the time for this design. Rolls Royce carried out the design in collaboration with the Whittle Laboratory.

The main objective of this research was to validate the understanding of suction side boundary layers under the influence of wakes. The data presented in this paper clearly illustrate that the presence of wakes shed from upstream blade rows dominates the boundary layer development. Under no circumstances can the boundary layer development be considered a steady process. This paper shows that the understanding of wake boundary layer interactions has been successfully employed in the new designs of the BR700 series LP turbines.

EXPERIMENTAL DETAILS

The measurement of wall shear stress using hot films was developed by Bellhouse and Schultz [14] 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 [15] and Davies and O'Donnell [16]. Also, 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 were used on the aft part of suction surfaces and were therefore likely to see laminar, turbulent, calmed and separated flow at different positions of the upstream rotor, see Halstead et al [17] or Banieghbal et al [18]. Calibration for all these conditions would be extremely difficult and quite probably impossible. It is for the above reasons that the hot film sensors are used in an uncalibrated form, which yields a pseudo shear stress. When used in an uncalibrated manner the absolute level of the shear stress is unknown, but it is the relative magnitude of the shear stress level from sensor to sensor that is obtained. With careful analysis, this relative or 'quasi' shear stress is all that is required to obtain information regarding the state of the boundary layers.

Figure 4 NGV2 of the BR715UHL LP turbine showing the hot film array of sensors on the right hand aerofoil.

The highest frequencies associated with turbulent fluctuations are thought to be of the order of 300kHz, whereas the frequency response of the hot film sensors is around 30-40kHz. Therefore, the majority of the turbulent fluctuations in the boundary layer cannot be measured. However, laminar, turbulent and separated boundary layers have very different shear stress levels. The changes in the levels occur at frequencies of the order of the wake passing of upstream rotors. This means that the hot film sensors can detect the passage of turbulent spots and their calmed regions as well as separated flows. The ability to measure these differing flow conditions and their relative robustness makes the hot film sensors a powerful measurement tool in a rig environment. No other instrumentation capable of unsteady measurement was available upstream of the NGVs. Therefore all the interpretation in this paper is made solely from CFD predictions (not shown) and the hot film measurements.

Past investigations into the development of blade surface boundary layers indicated that most of the interesting physics occurs from peak suction to the trailing edge of the profile. It is between these positions that the hot film sensors were located. The hot films were located at 40% span for NGV2 the BR710, BR715 and BR715UHL turbines. The films are located at 50% span for NGV3s on the BR715 and BR715UHL LP turbines. The occasional sensor failure is common on highly three-dimensional profiles due to difficulties with securing the hot film arrays to the curved surface of the blades. Figure 4 shows the NGV2 of the BR715UHL LP turbine with the hot film in position. Data from faulty sensors has not been shown, but the analysis of the flows was not hampered to any significant extent by such failures.

The data was ensemble averaged over 200 revolutions of the upstream rotor and logged at the rate of 125kHz for the BR710 and BR715 turbine tests. For the BR715UHL tests, 256 ensembles were taken at a rate of 80kHz for each sensor.

A variety of data processing techniques were employed to reduce the data. As well as the raw quasi shear stress τ_w, time mean values were also calculated. The ensemble RMS of a signal is a measure of the deviation from the ensemble mean of that signal. The ensemble skew of a signal distinguishes the positive or negative deviation of the signal at a particular time (measured relative to the reference time) from the mean of the signal at the same time. With hot film measurements, the skew of a signal is useful for detecting how far the boundary layer has progressed through transition (Hodson et al, [19]). If a boundary layer is completely laminar then the skew of the signal will be near zero. If it is predominately laminar with the occasional turbulent component then the skew of a signal will be small, but positive. Where the RMS is maximum (at an intermittency of approximately 50%) then the skew would be approximately zero. As the signal becomes turbulent with a smaller laminar component, the skew becomes negative. As the boundary layer becomes completely turbulent, the skew of a signal approaches zero. It is a characteristic of hot film gauge signals from transitional flows, that the positive skew, early in transition, is more obvious than the later negative skew.

RESULTS

BR710 High Lift demonstrator rig: Stage 2 Nozzle Guide Vane - CRUISE

The time history of the raw quasi wall shear stress measurements taken at the cruise condition are shown in Figure 5. The uppermost plot shows the measurements at 71% surface length. The lowest plot shows data from nearest the trailing edge of the blade at 96%s. The large upward spikes in shear stress are due to turbulent spots travelling over the sensors. The signals at 71%s, show turbulent spots, but little evidence of calmed flow. The quasi wall shear stress between these wakes (while not zero) probably indicates that this is near the position of separation. There are large fluctuations in the boundary layer at the final sensor indicating that transition is not complete at this Reynolds number. Calmed regions of flow can be seen at some locations, particularly those regions marked C, however, these calmed flow regions do not survive until the trailing edge of the profile.

The measurements within the ellipse show an interesting feature. There seems to be an absence of turbulent spots at the first sensor around the thirteenth wake. This allows separated flow transition to occur as wake induced spots are not present to disturb this process. The wake turbulence will obviously be present, so this separated flow transition cannot be considered to occur as it would in a steady environment. A frequency doubling of the fluctuations can be seen as the flow travels from the sensor at 88%s to 92%s which is often seen in separated flow transition, for example see Gostelow and Hong [20].

Figure 6 shows three ST diagrams. The black circles at the top of such plots indicate the position of the functional sensors. Plot (a) shows the non-dimensional ensemble mean quasi wall shear stress, (b) shows the ensemble RMS and (c) shows the ensemble skew. The relevant scales for each plot are located on the right hand side of the figure. The shear stress is made non-dimensional by the maximum value of shear stress measured by each sensor, i.e. $\tilde{\tau}(s,t)/\tilde{\tau}_{\max}(s)$, where *t* is time. This serves to enhance the periodic fluctuations in shear stress, but at the expense of their overall level. The RMS of the data is made non-dimensional by the maximum value of RMS measured at each sensor, i.e. $\tilde{\tau}'(s,t)/\tilde{\tau}'_{\max}(s)$.

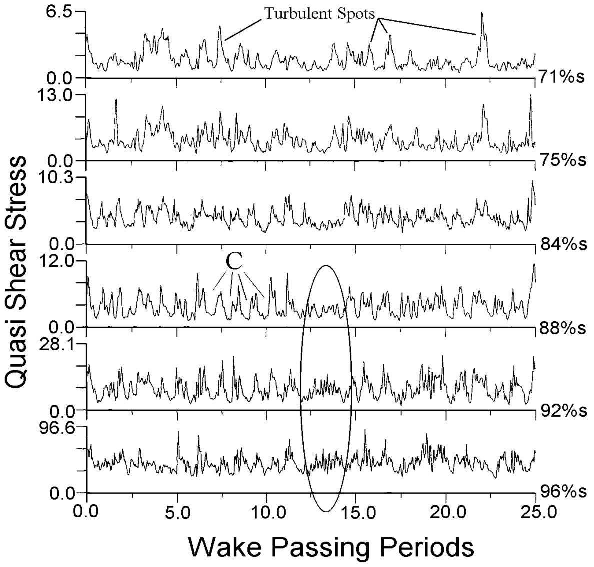

Figure 5 Time history traces of quasi wall shear stress for the cruise condition of the BR710 LP turbine.

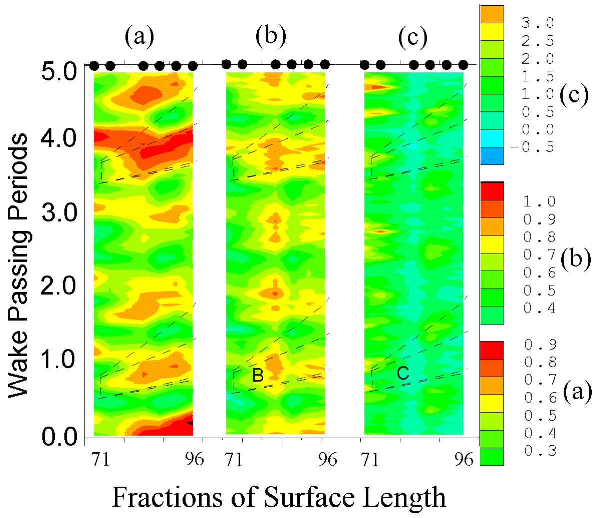

Figure 6 ST diagrams of (a) non dimensional ensemble mean quasi wall shear stress, (b) non dimensional ensemble RMS, and (c) ensemble skew.

Figure 6a shows a wedge shape region of high shear starting at approximately 71%s (within the dashed lines). The trailing edge of this wedge travels at approximately 50% of the local freestream velocity, while the leading edge travels faster at around 90%. The dashed lines on the figure correspond to these velocities and were calculated from a predicted velocity distribution. The final line (with the steepest gradient corresponds to the probable celerity of the calmed region. The calmed region is variously reported to travel at 30%U. The velocity distribution (not shown) also showed that boundary layer separation occurs at approximately 70%s, which is where wake induced transition starts to occur.

At the same phases and surface positions as regions of high quasi wall shear, one can see regions of high RMS, see 'b' and some regions of slightly negative skew in Figure 6 region 'c'. This is consistent with the interpretation that these regions are caused by transitional flow and are caused by the movement of turbulent spots over the sensors.

BR715 Engine Stage 2 Nozzle Guide Vane - TAKEOFF

The raw signals from the hot film sensors of the NGV2 of the BR715 LP turbine are presented in Figure 7. The signal from the sensor at 78%s is characteristic of a disturbed laminar (and mostly separated) boundary layer. Occasionally, a passing rotor wake causes transition to occur via the formation of a turbulent spot, but only in about 1 in 5 wake passings, at this Reynolds number and surface position. The sensors further downstream indicate that more turbulent spots have formed as the boundary layer becomes more receptive to the wake disturbances.

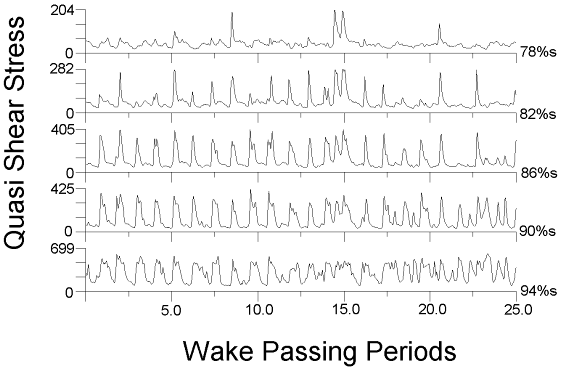

Figure 7 Raw Hot film data from NGV2 of the BR715 LP turbine

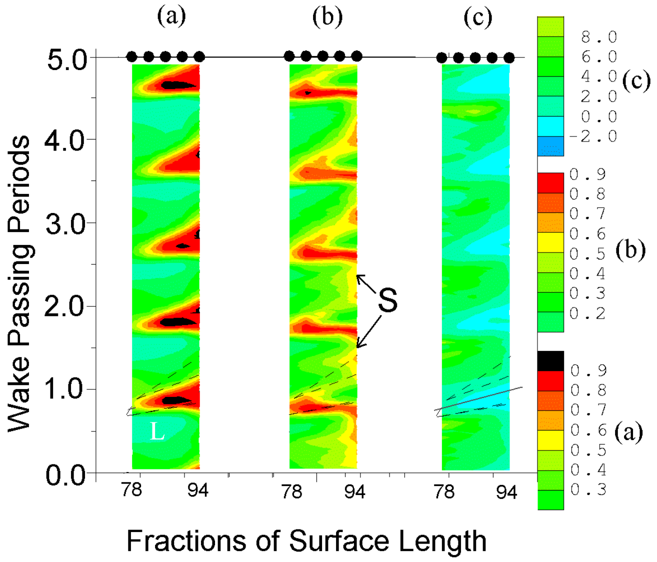

Figure 8 ST diagrams of (a) non-dimensional ensemble mean quasi wall shear stress, (b) non-dimensional ensemble RMS and (c) ensemble skew. Data is taken from NGV2 of the BR715 LP turbine.

Figure 8 presents data from this NGV as ST diagrams similar to those in figure 6. Wake induced transition occurs, on average, at 82%s as indicated by a wedge shaped region of high quasi wall shear (contours grey to black). The trajectories drawn onto the figure are those that correspond to the leading and trailing edges of turbulent spots. The final trajectory is the approximate velocity of the end of the calmed region. These trajectories have been calculated from predicted blade surface pressure distributions assuming constant values for the convection rates.

It is noted that near the leading edge the contours of ensemble mean, RMS and skew seem to travel faster than the local free stream velocity. It is believed that the wake causes transition by causing the formation of turbulent spots under its path. The wake convects at the local freestream velocity, but the spot's leading edge travels at approximately 0.9U. Therefore, the wake overtakes the spots it has formed, allowing it to form further spots ahead of the original ones. The wake then finds itself further downstream and over a region of flow that is more receptive to disturbances. Spots may also form under regions of the wake where the turbulence level is lower, that is, ahead of the wake centre line. In this way, the leading edge of the wake-affected zone may seem to travel faster than the free stream. Regions of high ensemble RMS (Figure 8b) and negative skew occur at the same positions in time and space as those of high shear. This is consistent with the interpretation of wake induced transition occurring at 78%s. Regions of high ensemble RMS seem to occur just before the arrival of each wake. This could be separated flow transition starting to occur as it starts after the calmed region of the previous spots have passed, see Regions marked 'S'.

Both NGVs of the BR710 and BR715 engines show classical wake induced transitional behaviour of the boundary layers. NGV2 of the BR715UHL also shows this behaviour but the data has not been presented for brevity.

BR715 Engine Stage 3 Nozzle Guide Vane - Cruise

Figure 9 shows the variation in time mean quasi wall shear stress variation over the surface of NGV3 of the BR715 LP turbine at the cruise condition. The shear stress starts relatively high and drops as the boundary layer thickens despite the flow acceleration. After the minimum at 75%s, the shear stress increases due to the boundary layer undergoing transition. This increases the amount of turbulent flow at each sensor location and therefore the mean level of quasi wall shear stress. Computational predictions showed that time mean position of boundary layer separation occurs at approximately 65%s.

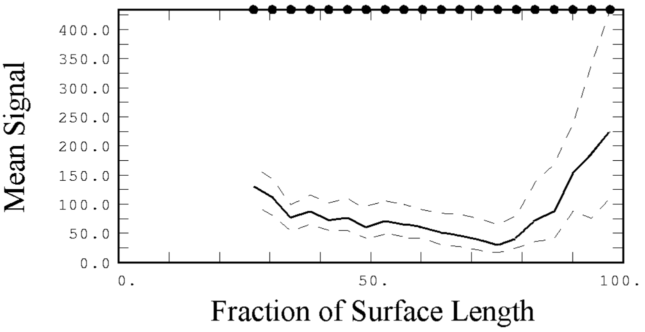

Figure 9 Variation of time mean (solid lines) and the envelope of the ensemble mean quasi wall shear tress for NGV3 of the BR715 LP turbine.

Figure 10a shows regions of high ensemble mean quasi wall shear (marked 'H2') originating at 75%s. These are caused by (and occur at the wake passing frequency of) the wakes shed from rotor 2. The regions marked 'H4' are not in fact regions caused by the high shear in turbulent spots. They are simply the response of the laminar boundary layers to the passage of wakes in the freestream. Because of the method of making the data non-dimensional, the levels of the regions H4 and H2 are the same colour, however, they are very different levels. The mean quasi wall shear stress in Figure 8 shows that the mean shear stress is decreasing in this region. The RMS (not shown) of this data is almost constant up to peak suction in these locations and the skew (also not shown) is also near zero. The conclusion is that wake transition occurs in the region of laminar separation and not before.

Figure 10b shows data for the same condition but at a different position of the upstream rotor. Again the regions marked ‘H2’ are seen, but there are also other regions marked ‘H1’, which are stronger than those in Figure 10a, and are of only a slightly lower quasi wall shear that those marked ‘H2’. They show that transitional activity occurs at these surface positions, for certain positions of the upstream rotor. Therefore, there are two regions of transitional activity and which occur at rotor 2 blade passing frequency. A possible explanation for this is the following. The first transition region seen in the ST diagrams (‘H2’) is caused by Rotor 2 and occurs at 75%s. The other transition region is caused by wakes from NGV2 that pass through Rotor 2 (region ‘H1’). Rotor 1 in turn modulates NGV2 wakes. The difference in blade counts for Rotor 1 and Rotor 2 leads to the low frequency beating (modulation), whereby at some Rotor 2 positions the strength of the second transition region is diminished. The amplitude-modulated wakes are distorted as they travel through NGV3, which makes interpreting the data more difficult.

This beating in this data is similar to that measured by Ardnt [21]. In that investigation Arndt showed that rotor 1 and rotor 2 interactions gave rise to amplitude modulations of the strength of the wakes that entered NGV3. Regions marked ‘H1’ reduce in strength as they reach the start of regions ‘H3’ because they are older turbulent boundary layer. New turbulent boundary layer is formed at ‘H2’, which has a higher quasi wall shear stress.

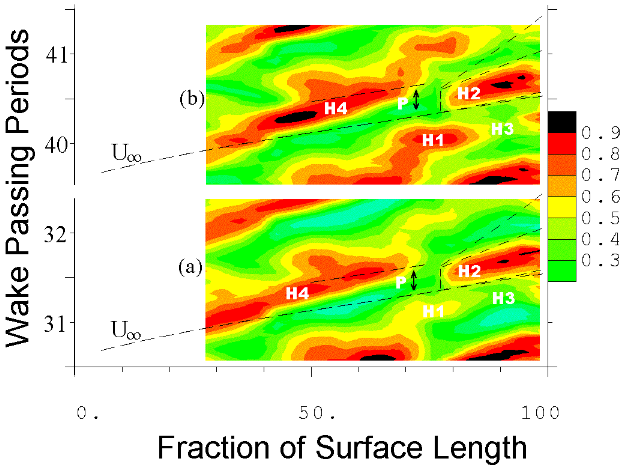

Figure 10 ST diagrams of non-dimensional ensemble mean quasi wall shear stress from NGV3 of the BR715 LP turbine. Cruise conditions

Figure 11 shows the variation of quasi wall shear stress for a hot film sensor located at 71.5%s on NGV3 for a complete revolution of rotor 2. It can be seen that there is a variation in the amplitude of shear stress from the interference in region A, to the reinforcement that occurs in regions B. The variation of shear stress is a consequence of the changes in turbulent spot production rates that occur because of the beating effect. Wakes with high turbulence intensity are likely to cause the higher shear stress regions circled in region ‘B’. Arndt [21] carried out measurements with a hot film probe traversed upstream of the inlet of NGV3 from an MTU LP turbine and observed a similar beating of the inlet turbulence field.

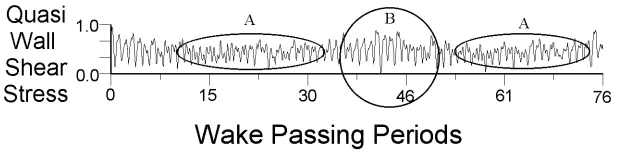

Figure 11 Ensemble mean data for one revolution of rotor 2 of the BR715 LP turbine.

BR715U Engine Stage 3 Nozzle Guide Vane - Cruise

The final hot film measurements are taken from the BR715U LP turbine. These show similar results as from the 3rd stage NGV in the BR715 turbine but it should be remembered that blades on this LP turbine generate 12% more lift than the BR715 turbine.

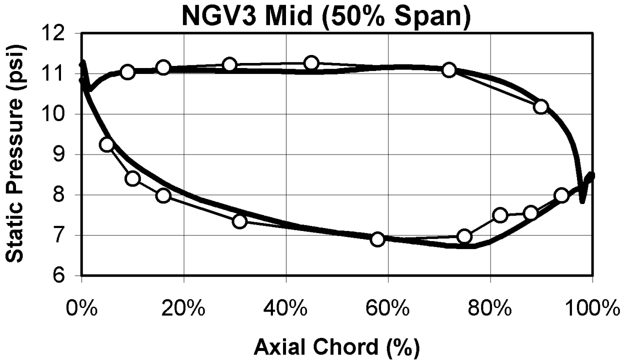

Figure 12. Predicted (solid line) and measured (circles) static pressures on NGV3 of the BR715U LP turbine. Cruise conditions. After Haselbach et al [13].

The measured and predicted pressure distributions for this profile are shown in Figure 12. The measured static pressures show at pressure plateau and therefore boundary layer separation starting at approximately 82% axial chord. This is a little later than the hot film measurements will have us believe. However, given the few static pressure tappings available in this rig, it is not unreasonable that there is a difference.

The time history of the raw data for various sensors along the surface can be seen in Figure 13. There is no obvious evidence of individual turbulent spots or indeed calmed regions. Other data (Ramesh, [22]) taken in low speed tests has also shown that the boundary layers on ultra high lift profiles do not seem to exhibit as much calmed flow near the trailing edge as lower lift profiles. This does not necessarily mean that calmed regions do not exist in these flows; it just means that they are not obvious from raw data. Further examination of these figures shows that there is little periodicity in the raw data, however wake-passing events can be seen in some of the data presented in the skew data in Figure 14. The lack of periodicity in the flows on this turbine is believed to be caused by the strong separated flow transition present. Cascade measurements on ultra high lift LP turbines have shown that the separation bubbles and their transition can dominate the flows on these blades, Howell et al [2] and Ramesh [22]. It is believed that in this case, the wakes simply modulate the separated flow transition process and so the wake induced transition is not easily seen from hot film measurements alone.

The ST diagrams of this data show wake-induced transition occurring more clearly than the raw data of previous plots. For example, see the ensemble mean quasi wall shear stress data in

Figure 15 and in particular regions marked 'H1' and 'H2' – these mark the onset of wake induced transition. This occurs at approximately the separation location of the boundary layer.

The blade numbers for this turbine are different to the previous one and no beating could be seen in the data. Again, this is not to say that beating does not occur, but it could be that it is disguised by the separated flow transition, which seems to be the dominant transition mechanism.

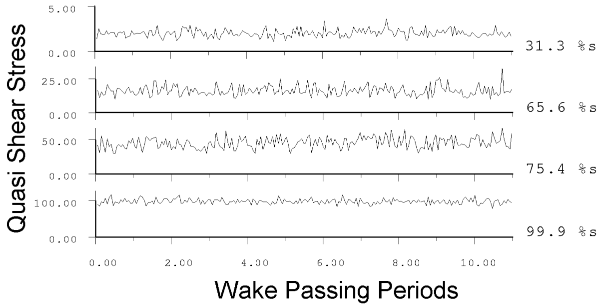

Figure 13 Time history of the raw data

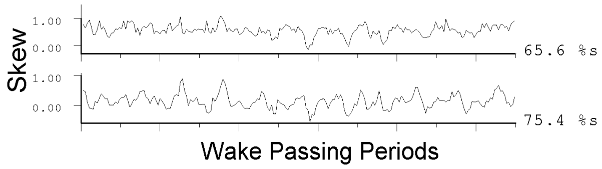

Figure 14 Ensemble mean skew for to sensors showing the change in periodicity of the data as the flow travels down stream.

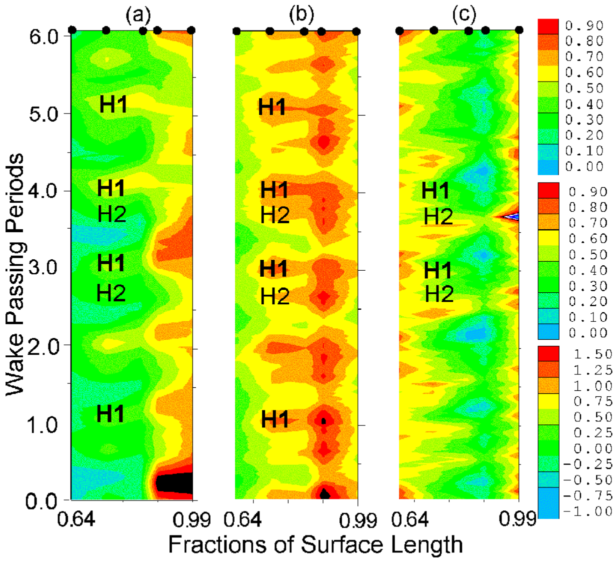

Figure 15 ST diagrams of (a) non-dimensional ensemble mean quasi wall shear stress, (b) non-dimensional ensemble RMS and (c) ensemble skew. Data is taken from NGV3 of the BR715U LP turbine.

The doubling of the wake passing reduced frequency (seen in Figures 10 and 15), which the 3rd stage NGVs are subjected can be considered beneficial, particularly for the ultra high-lift profiles. 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, see Howell et al [2]. In the first few stages, there are fewer blade row interactions, but as Howell et al [2] showed, one does not desire reduced frequency doubling as this increases losses.

Comparison with Low Speed Data

Having described some of the salient details of the data from the high-speed rigs, it is now appropriate to compare these measurements to some take from a low speed facility designed to simulate the presence of an upstream rotor.

Figure 16 shows ST diagrams of non-dimensional ensemble mean quasi wall shear stress data from both second stage NGVs from the LP turbines already discussed and also from a low speed high lift blade. The low speed profile is described by Curtis et al [3] and is denoted profile H. Measurements from the low speed profile capture all the important features that are seen in the high-speed measurements. The onset location of wake-induced transition is shown as a region of high shear stress denoted 'W'. This region forms a wedge shaped that is bounded by the trajectories of the leading and trailing edge of turbulent spots.

Separated flow transition can be seen occurring (between the wakes) on the low speed profile and BR710 profile. The last sensor on the BR710 profile was located at 94%s, whereas the last sensors on the other profiles were at around 96%s. If separated flow transition occurs late on the blade, then the sensors on BR715 profile may not be far enough back along the surface to measure this. The data from NGV2 of the BR715UHL turbine shows very similar features to NGV2 of the BR715 turbine and so has therefore not been shown.

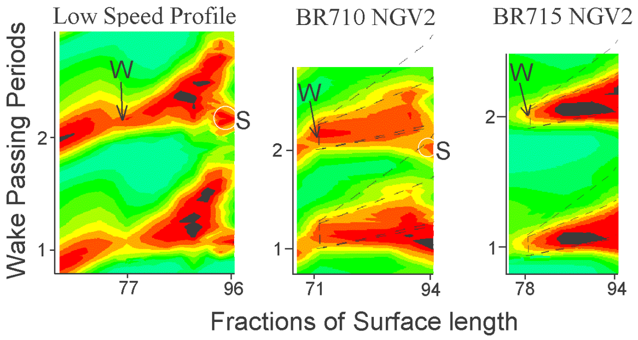

Figure 16 A comparison of low speed and high speed measurements of ensemble quasi wall shear stress from various profiles.

The low shear regions caused by the spot's calmed regions can be seen in the raw data of all measurements. The wake passing frequency of the high speed rigs was of the order of 3kHz, but for the low speed measurements the frequency is just 60Hz. The frequency response of the hot films was the same for both regimes. The low speed measurements therefore allow a much larger number of samples to be taken per wake passage. This gives better quality data, allows much better analysis and illustrates the advantage of taking measurements in low speed rigs. This type of moving bar wake generator cannot simulate an upstream stator row because the moving bars do not turn the flow. However, their use in gaining the highest quality data with relative ease and allowing parametric studies is obvious.

CONCLUSIONS

Boundary layer separation occurs on NGV2 of the 710 LP turbine rig soon after peak Mach number, and reattach before the trailing edge. At cruise Reynolds numbers, wake induced transition starts at around the separation position, but separated flow transition is not complete by the trailing edge. Calmed regions can be seen in much of the data of this conventional lift LP turbine.

Results from NGV2 of the BR715 LP turbine rig show periodic wake induced transition starting at around 71%s. Flow separation occurs near the same position but only between wake induced transition regions. Calmed regions can be seen in much of the data, even at the trailing edge. It is possible that there is an open separation at the trailing edge at some rotor positions and at the Reynolds number shown, but on average (in time) the trailing edge flow is attached.

The results from NGV3 of the BR715 LP turbine are far more complicated than those for NGV2 of the same turbine. This blade row is subjected to a more disturbed flow, as there is another stage ahead of it. Wake induced transition (caused by Rotor 2) occurs at around 75%s. A wake transition region occurs between those caused by Rotor 2, and is probably caused by NGV2 and a combination of NGV1, and Rotor 1 causing a beating frequency with Rotor 2. RMS and skew data are consistent with this interpretation.

The results from NGV3 of the BR715U LP turbine are similar to those of the same NGV on the BR715 LP turbine, except that the separated flow transition seems to dominate the flow. This is probably due to the increased deceleration used on these profiles used to generate the increased lift. There is an absence of the beating in the BR715U turbine data. The beating is almost certainly present, but is could be that the separated flow transition tends to disguise this.

The most important features of the measurements from the second stage NGVs of all the high-speed turbine rigs are present in the low speed low speed rigs. It is with results from low speed rigs tests that the physical understanding of wake boundary layer interactions has been obtained. This in turn has provided the firm base on which to develop the high and ultra lift profiles presented.

None of the flows on these NGVs can be considered steady. Therefore, design methods that neglect the unsteady effects of wakes are completely incapable of predicting the flows. As design envelopes are pushed further (in terms of lift) it will be a requirement that design methods can predict these unsteady features.

This paper has shown that through a program of mainly low speed experimental research, a good understanding of the interactions of wakes turbulence and boundary layers has been developed. From this knowledge, incremental steps have been taken that has allowed the development of ultra high lift profiles. The effects of multistage interactions have also been understood and it is believed that this understanding can help in the design of future multistage machines, particularly at low Reynolds numbers.

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