18th Australasian Fluid Mechanics Conference
Launceston, Tasmania
Australia, 3-7 December 2012

The Effect of Stator Reduced Frequency on Transition and Separation at the Leading Edge of a Compressor Stator

S. C. T. Perkins and A. D. Henderson

School of Engineering
University of Tasmania, Tasmania 7001, Australia

Abstract

Studies on the effect of stator reduced frequency in low pressure turbines have shown that periodic wake-induced unsteadiness can increase blade element circulation and reduce losses by up to 15% when compared to steady flow operation. This is primarily due to suppression of a large separation bubble that forms downstream of peak suction under steady conditions, and this is periodically suppressed by wake passing events resulting in significantly reduced losses generated within the boundary layer.

This research examines the effect of wake induced unsteady flow on a controlled diffusion (CD) compressor stator blade with circular arc leading edge. The blade profile is tested inside a large scale two-dimensional cascade, which is fitted with a traveling bar mechanism to produce wakes similar those generated by an upstream rotor blade row. The flow is seen to experience flow separations and subsequent transition at the leading edge on both the pressure and suction surfaces due to a velocity overspeed caused by discontinuities in surface curvature.

Testing was carried out at reduced frequencies of 0, 0.47, 0.94 and 1.88 at the design inlet flow angle of 45.5^o. The Reynolds number based on chord was $230,000$ and the average freestream turbulent intensity was 4.0%.

A range of experimental measurements were used to study the stator's performance: high resolution time-averaged blade surface static pressure measurements; inlet and exit 3-hole probe traverses and triggered data acquisition from an array of surface mounted hot-film sensors. Results from the hot-film sensors were subsequently interpreted to yield quasi-wall shear stress (QWSS) and turbulent intermittency, and ensemble averaged statistics are presented.

Results show that increasing stator reduced frequency from 0 to 1.88 increases the overall blade pressure loss. The losses generated on the pressure surface and suction surfaces differ significantly. The pressure surface demonstrate a clear reduction in loss with an increase in reduced frequency whereas the opposite trend was seen on the suction surface.

Wake-induced turbulent strips were observed to suppress the formation of a leading edge separation bubble that forms under steady flow conditions on the suction surface, and also between wake passing events. These strips reduced in width and level of turbulent intermittency through the favorable pressure gradient leading to peak suction and grew in the adverse pressure gradient of the velocity overspeed. The flow between wake-induced turbulent strips partially relaminarises through the favorable pressure gradient leading to peak suction.

Introduction

Volino [10] studied the effect of changing wake passing frequency with high and low free-stream turbulence conditions at two Reynolds numbers. At low wake passing frequencies the boundary separated between wakes was investigated under steady flow conditions. At increased Reynolds number and freestream turbulence level, a lower reduced frequency was required to largely suppress the separation. This supports previous studies that showed increasing Reynolds number and freestream turbulence level reduces the likelihood of a boundary layer separation and increases the likelihood of reattachment once separated. Turbulent wakes were also shown to effectively suppress a boundary layer from separating [8, 2, 5].

Howell [4] investigated the effect of varying reduced frequencies with an ultra high lift LP turbine blade profile inside a cascade. The results showed that as the reduced frequency and Reynolds number were increased, a significant decrease in blade loss was seen. Five reduced frequencies were tested ranging from $0-1$ over a range of Reynolds numbers from $Re_c = 70,000-210,000$ and the profile loss was seen to decrease by up to a factor of approximately 2.5. Howell [4] showed that if this is exceeded the benefits gained from suppressing separated flow regions become outweighed by the increase in the proportion of the blade surface covered by wake generated turbulent flow (Figure 1). A similar effect was seen when artificially generated turbulent spots were convected through a separated shear layer.

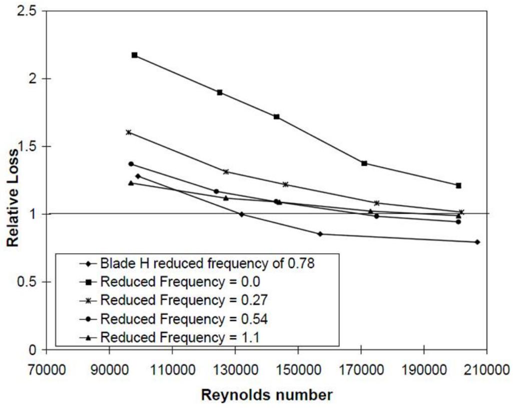

Figure 1: Effect of Reynolds number and reduced frequency on LP turbine blade profile loss [4]

The current study aims to identify the effect of varying the stator reduced frequency on a compressor blade at a fixed flow coefficient near design point operation and to identify how this change influences boundary layer development and blade pressure loss.

Experimental Measurements

A large scale 2D linear compressor cascade was used to simulate the flow through a compressor stator blade row. The cascade in the Whittle Laboratory at the University of Cambridge comprised of 5 blade passages: four whole blades and two half blades to complete the top and bottom passages (Figure 2). The

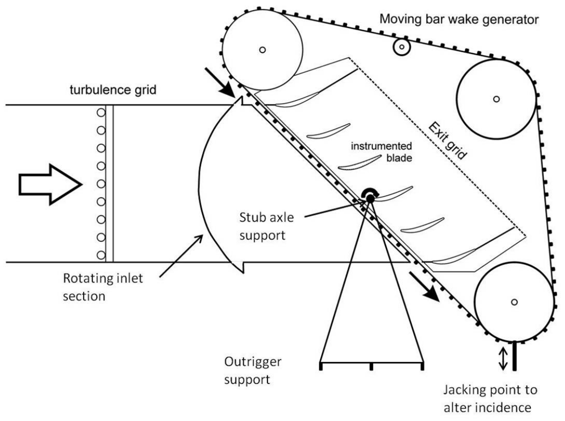

Figure 2: Schematic diagram of the 2D cascade

blade profile is based on a CD stator blade previously studied in a 1.5 stage low-speed axial research compressor at the University of Tasmania (UTAS) [3].

Each blade in the cascade has a chord length of 285 mm, a pitch spacing of 280 mm and a span of 600 mm giving a solidity of 0.99 and an aspect ratio of 2.1. The design inlet flow angle was 45.0^o and the maximum achievable Reynolds number under unsteady operation was $Re_c = 230,000$. The instrumented blade was manufactured using a Stereo Lythograph printer which had a documented tolerance of 32 μm in the orientation chosen (0.01% chord). The blade was then carefully finished with fine wet and dry paper by hand to achieve a smooth surface finish.

A total of 194 surface pressure tappings were placed around the blade profile to measure the overall static pressure distribution, 104 of which were located on the suction surface and concentrated between $S^* = 0 - 0.1$, where S^* is the ratio of surface distance from leading edge to total surface length.

Inlet and exit traverses were carried out using two custom made three-hole cobra type pressure probes to determine the distribution of flow angle, velocity and total pressure at the inlet and exit of the cascade. These were also used to evaluate blade pressure loss and to check the periodicity of the cascade about the instrumented blade. Time mean blade pressure loss is defined as $\bar{\omega} = \frac{P_{o1}-P_{o2}}{P_{o1}-P_{s1}}$.

The reference dynamic pressure was measured with an accuracy ±1.5 Pa, corresponding to a maximum uncertainty in pressure measurement of ±1.4% at $Re_c = 260,000$. Repeated measurements of blade pressure loss at various points in the loss loop were used to estimate maximum uncertainty of ±2.5% for a consistent average velocity density ratio (AVDR) between test measurements.

An array of surface mounted hot-film sensors were mounted on the blade's leading edge. Triggered raw bridge voltage traces were simultaneously acquired from a 15 channel Dantec Streamline system at a sampling frequency of 60 kHz. A total of 512 records were used to produce ensemble average QWSS ($\tau_q = \left(\frac{E^2-E_o^2}{E_0^2}\right)^3$) and turbulent intermittency. These results were used to determine the time averaged turbulent intermittency using a hybrid threshold peak-valley-counting algorithm developed by [9].

Scope of Investigation

Initial testing was intended to allow comparison with compressor studies by Henderson [3]. Three stator reduced frequencies were tested: $\omega_s = 0.47, 0.94$, 1.88 as well as the steady flow case, at an inlet flow angle of $\alpha_1 = 45.5^o$, Reynolds number based on blade chord of $Re_c = 230,000$ and a freestream turbulence intensity of 4.0% at the leading edge plane of the instrumented blade. This is a widely accepted value typical for a embedded stage in a multistage machine [7, 1]. Stator reduced frequency $\omega_S = \left(\frac{\sigma_s \cos(\alpha_1)}{\phi}\right)\left(\frac{s_s}{s_r}\right)$ where σ_s is the stator solidity, s_s is the stator pitch and s_r is the rotor pitch.

Results and Discussion

Expected Steady Flow Performance

Steady flow testing by Perkins [6] showed that in steady flow a small separation bubble forms at the leading edge at slightly different conditions (an inlet flow angle of $\alpha_1 = 45.5^o$ and $Re_c = 230,000$), triggering rapid transition of the boundary layer before the favorable pressure gradient of the suction surface partially relaminarises it from approximately $\gamma = 1 - 0.5$.

The expected formation of a leading edge separation bubble and transition was supported by numerical modelling, which predicted a leading edge separation bubble at the leading edge of both surfaces under both sets of steady conditions mentioned above. The separation bubble is slightly smaller for $Re_c = 230,000$ compared to the $Re_c = 260,000$ case at the same inlet flow angle and freestream turbulence level.

Influence of wakes on boundary layer development

A contour plot of ensemble averaged turbulent intermittency at a reduced frequency of $\omega_s = 0.94$ is displayed in Figure 3, which immediately demonstrates the transitional nature of the leading edge boundary layer under the influence of unsteady wake passing events. Wake passing events captured in each ensemble are consistent and spaced equally in time. A wake induced turbulent strip is visible from the leading edge to the end of the hot-film sensor array on both surfaces and clearly display an elevated level of intermittency compared to the surrounding flow.

A strip of elevated turbulent intermittency ($\gamma = 1$) forms in the decelerating portion of the spike during and between wake passing events (Region 3 shown in Figure 3) where the laminar separation bubble formed under steady flow conditions. This turbulent strip is followed by significant relaminarisation through the favorable pressure gradient of the suction surface where γ reduced from close to unity to approximately 0.5 (4 - Figure 3).

In the two regions of accelerating flow on the suction surface (Regions 1 and 2 in Figure 3) between the stagnation point and the peak of the velocity spike, and also downstream of the velocity spike leading to peak suction (Region 4) there is a narrowing of the wake induced turbulent strip. The opposite is observed in regions of decelerating flow (Region 3 Figure 3) with the wake induced turbulent strips spreading in a spanwise direction. The wake passing events are thinnest at the peak of the velocity overspeed following the extreme favorable pressure gradient and are widest at the end of the adverse pressure gradient of the leading edge velocity overspeed.

The favorable pressure gradient of the suction surfaces changes significantly between the end of the velocity overspeed and peak suction. Of particular note is the region between $S^* = 0.045 - 0.08$ (S^* is the ratio of surface length measured from the leading edge to total surface length), where Figures 4 shows a steep increase in pressure gradient at $S^* = 0.045$, which coincides with a rapid decrease in intermittency and coincides with the leading edge separation bubble reattachment zone. Downstream

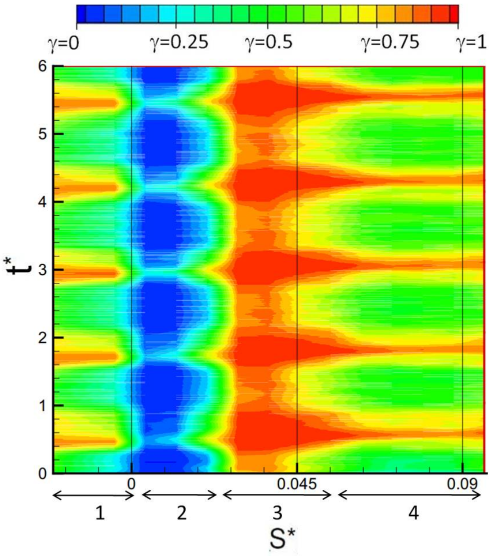

Figure 3: Ensemble average distribution of turbulent intermittency in the leading edge region at $\alpha_1 = 45.5^o$, $Re_c = 230,000$ and $\omega_s = 0.94$ in the compressor cascade. The blade surface has been classified into Regions 1-4 to aid interpretation of the flow (t^* - non-dimensional time)

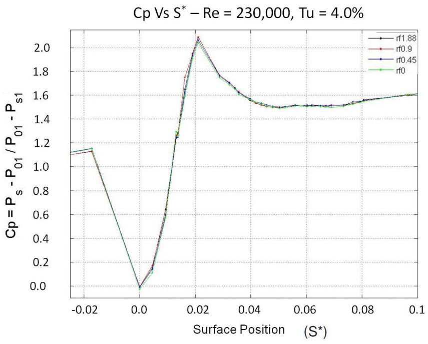

Figure 4: Time averaged effect of passing wakes on the leading edge velocity over-speed to the compressor cascade stator blade row

of $S^* = 0.08$ the pressure gradient relaxes, which results in not only a mild increase in intermittency, but also a widening of the wake induced turbulent strips. The relaxation was also observed in plots of time averaged plots where a decrease in time average QWSS was observed, which is connected with an increase in boundary layer thickness in an mildly accelerating flow.

Effect of Stator Reduced Frequency on Blade Pressure Loss

Blade pressure loss is an important measure of blade performance, especially when making comparisons between different machine operating points. Figure 5 shows how the nominal time average blade pressure loss varies with an increase in stator reduced frequency from $\omega_s = 0 - 1.88$ at a fixed flow coefficient of $\phi = 0.675$.

The steady flow measurements of Perkins [6] noted above clearly shows a separation bubble on both blade surfaces initiates transition just downstream from the leading edge in the adverse pressure gradient of the spike. The pressure surface remains in a fully turbulent state to the trailing edge whilst the suction surface has a large turbulent patch in the separation bubble's reattachment zone at the end of the leading edge velocity spike, before relaminarising to a value of approximately $\gamma = 0.65$ in the favorable pressure gradient leading to peak suction. As the favorable pressure gradient relaxes further along the surface, transition to fully turbulent flow occurs in the region close to peak suction. A trailing edge separation did not form.

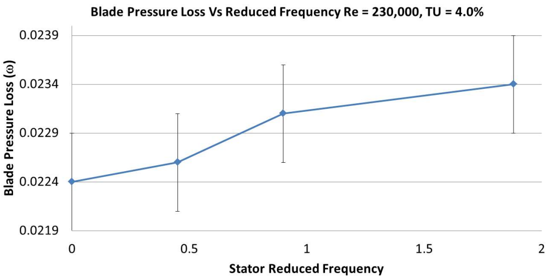

Figure 5: Effect of reduced frequency on blade pressure loss of a compressor stator blade row

Figure 6 helps identify how the overall blade pressure loss is distributed between the pressure and suction surfaces, which is important when identifying the main mechanisms behind loss generation under varying operating conditions. From Figure 6, a definite trend is present on both surfaces. The influence of increasing the stator reduced frequency has an opposite effect on each surfaces of a CD stator with a circular arc leading edge.

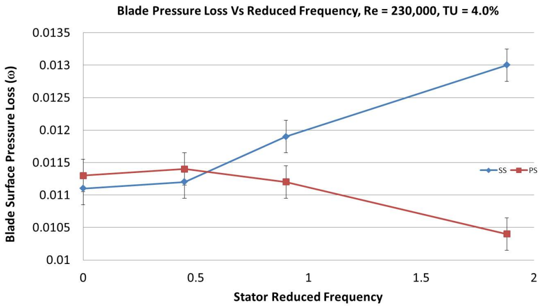

Figure 6: Breakdown of loss generated by the suction surface (SS) and pressure surface (PS) of the blade

Pressure Surface Loss

When moving from a steady to an unsteady flow environment at a stator reduced frequency of $\omega_s = 0.44$, the loss generated by the pressure surface remains almost constant.

Downstream of the leading edge the pressure surface boundary layer is fully turbulent and remains in that state to the trailing edge.

Wake passing events and turbulent spots are known to suppress the formation of separation bubbles: a leading edge separation bubble was present under the current test conditions in steady flow. The periodic suppression of the leading edge bubble reduced the local rate of loss generation compared to that under steady flow conditions.

As the reduced frequency is increased from $\omega_s = 0.44$ to 0.9 and 1.88 there is an almost linear decrease in blade pressure loss generated by the pressure surface. The increase in reduced frequency decreases the amount of time the leading edge separation bubble has to re-form between wake passing events and thus decreases the ensemble average loss generation in this region.

Suction Surface Loss

On the suction surface pressure loss follows an almost identical, but opposite trend to that seen on the pressure surface when introducing periodic unsteadiness at a stator reduced frequency of $\omega_s = 0.44$.

At a reduced frequency of $\omega_s = 0.44$ a wake induced turbulent strip is present on the surface 44% of the time resulting in the blade having no influence from a wake passing event for 66% of the time - during which the blade resumes a similar characteristic to that seen in steady operation.

A separation is expected to form, in between wake passing events, where the flow resumes a steady flow-like intermittency distribution. During a wake passing event the separation bubble is suppressed, as the wake convects through the leading edge region, resulting in a local reduction in leading edge momentum thickness - corresponding to a decrease in blade pressure loss. The potential decrease in loss is offset as the turbulent wake leads to an increase in the time averaged turbulent wetted area on the suction surface. This increases the loss produced over the front half of the blade, which, between wake passing events was transitional and caused relaminarisation to occur in the favorable pressure gradient. The turbulent patch is followed by the same calmed region mentioned previously.

Increasing the reduced frequency increases the amount of time the blade is influenced by a wake passing event.

As ω_s is increased to 0.9 and 1.88 the loss produced by the suction surface increases in an almost linear fashion. At a reduced frequency of $\omega_s = 1.88$ the blade is in contact with 1.88 wakes at any one time. The increase in loss is as a result of the increase in turbulent wetted area on the blades surface caused by wake passing events that have no capacity to suppress separations on the surface and thus reduce blade loss.

If the inlet flow angle was increased such that under steady operation a leading edge separation bubble formed on the blade, causing transition to occur at the leading edge, then the influence of wakes could be beneficial and reduce the pressure loss on the suction surface as was seen previously to occur on the pressure surface. The same result could be achieved at large values of negative incidence where a separation bubble forms downstream of peak suction.

Conclusions

This investigation has demonstrated that at near design conditions increasing stator reduced frequency increases blade pressure loss. Moving past $\omega_s = 0.47$ increases the proportion of loss generated by the suction surface whilst decreasing that generated on the pressure surface.

On the suction surface, quasi-wall shear stress traces show an increase in turbulent activity between wake passing events with a decrease in reduced frequency, which is coupled with a reduction in wake induced turbulent wetted area due to an increase in wake passing period. Over the front portion of the blade flow between wake passing events is transitional and relaminarising in the favorable pressure gradient leading to peak suction. Wake-induced turbulent strips suppress the leading edge separation bubble present under steady flow conditions and in between wake passing events. The influence of this is likely to be minimal as the separation bubble that forms on the suction surface is small.

The pressure surface demonstrates a clear reduction in loss with an increased reduced frequency. Downstream of the leading edge separation bubble a fully turbulent boundary layer covers the blade's surface to the trailing edge. The increased periodic suppression of the leading edge separation bubble is expected to contribute to the decrease in pressure surface loss with an increase in reduced frequency. As the boundary layer is fully turbulent, a decrease in local loss production will also be seen in the calmed zone following a wake passing event.

It is expected that trends seen at near design incidence would change considerably under off design conditions, particularly at positive incidence where a large separation bubble forms under steady conditions leading to a large increase in local loss generation. Under such conditions an increase in stator reduced frequency should reduce the increase in loss with reduced frequency and at large values of inlet flow angle could create a reversed trend similar to that seen on very high lift turbine blades.

References

[1] Camp, T. R. and Shin, H. W., Turbulence intensity and length scale measurements in multistage compressors, *Journal of Turbomachinery*, **117**, 1995, 38 – 46.

[2] Curtis, E. M., Hodson, H. P., Banieghbal, M. R., Denton, J. D. and Howell, R. J., Development of blade profiles for low pressure turbine applications, in *ASME Paper 96-GT-358*, 1996.

[3] Henderson, A. D. and Walker, G. J., Observations of transition phenomena on a controlled diffusion compressor stator with a circular arc leading edge, *Journal of Turbomachinery*, **132**, 2010, 1 – 9.

[4] Howell, R. J., *Wake-separation bubble interaction in low Reynolds number turbomachinery*, Ph.D. thesis, Whittle Laboratory, Cambridge University, 1999.

[5] Howell, R. J., Ramesh, O. N., Hodson, H. P. and Schulte, V., High life and aft loaded profiles for low pressure turbines, in *ASME 2000-GT-261*, 2000.

[6] Perkins, S. C. T. and Henderson, A. D., Separation and relaminarisation at the circular arc leading edge of a controlled diffusion compressor stator, *Proceeding of ASME Turbo Expo 2012, GT2012-69384*.

[7] Place, J. M. M., Howard, M. A. and Cumpsty, N. A., Simulating the multi-stage environment for single-stage compressor experiments, *Journal of Turbomachinery*, **33**, 1996, 706–716.

[8] Schulte, V. and Hodson, H. P., Wake-separation bubble interaction in low pressure turbines, *AIAA/SAE/ASME/ASEE 30th Joint Propulsion Conference*, **30**.

[9] Solomon, W. J., *Unsteady Boundary Layer Transition On Axial Compressor Blades*, Ph.D. thesis, University of Tasmania, 1996.

[10] Volino, R. J., Effect of unsteady wakes on boundary layer separation on a very high lift low pressure turbine airfoil, *Proceedings of ASME Turbo Expo 2010*.