Abstract

In this paper an investigation on the interaction of incoming turbulence with the separation bubble on a low pressure turbine blade is investigated. Two cases are considered where for one case uniform homogeneous turbulence is introduced and in the other case discrete wakes are interacting with the flow around the blade. In order to investigate the coupling mechanisms the flow prior to the separation, the Kelvin–Helmholtz rollers and the flow at the trailing edge where Karman vortex shedding occurs are correlated with each other. In the homogeneous inflow case the suction side separation point location shows a dependence on the trailing edge vortex shedding while with discrete incoming wakes this is not the case. In addition the correlation of the Kelvin–Helmholtz rollers with the flow beneath them is investigated. It is found that the vortex shedding that develops due to a Kelvin–Helmholtz instability of the separation bubble is suppressed by the strong turbulence of an incoming wake, but that the bubble shedding mechanism recovers between subsequent wakes. Using conditioned correlations, a strong coupling of the Kelvin–Helmholtz rollers with the blade surface has been identified for the case with homogeneous inflow turbulence.

Introduction

Flow through a low-pressure turbine (LPT) is strongly influenced by unsteady interactions of blade rows moving with respect to each other [2]. One of the major mechanisms is the influence of wakes shed at the trailing edge of a blade with the downstream row. Axial gaps typical of LPTs are too small for the wakes to mix out before entering the downstream blade rows. Due to the relative velocity in the circumferential direction the downstream row experiences a time-periodic alteration between flow from the wake region and flow from the free-stream region. With respect to the free-stream the wake flow generally has higher turbulence level. In addition the momentum deficit of the wake flow in conjunction with the circumferential velocity between subsequent blade rows leads to a tendency of the wake fluid to move towards the suction side surface, a mechanism often referred to as “negative jet” [4]. These phenomena in general lead to a strong interaction of the wake fluid with the suction side boundary layer [8].

For typical LPTs in aircraft engines at cruise the Reynolds number is in the range of 50,000 to 250,000. For blades at the lower end of that range the boundary layer is laminar for a significant part on the blade surface, and due to the strong adverse pressure gradient in the aft section of the suction side is subject to laminar separation. In fact for current designs of low Re LPTs it is common to increase the load (because this decreases the blade count, weight and cost of the engine) to a point where the flow undergoes laminar separation and forms a small separation bubble [2] which does not significantly affect kinetic losses, in contrast to large separation bubbles. Where reattachment of the flow occurs is determined by the transition process of the separated shear layer, which is subject to an inviscid Kelvin–Helmholtz (KH) type instability that results in spanwise coherent KH rollers.

It has been shown [1] that various “routes to transition” exist for typical LPT flows. For cases that show a laminar separation on the suction side of the blade, inlet disturbances (characterized either as discrete events like wake or uniform turbulence originating from wakes further upstream that already have mixed out) have a strong effect on the breakdown of the KH rollers. Two mechanisms dominate in these cases. Firstly, a direct interaction of incoming turbulent structures with the KH rollers leads to spanwise chopping and subsequent breakdown. Secondly, the inflow disturbances create turbulent spots in the initial boundary layers of the blade that develop into Klebanoff streaks and destabilize the separated shear layer and thereby accelerate transition. The latter mechanism in general delays separation with respect to a case with laminar boundary layers. While general mechanisms have been identified and the influence of the inlet structures has been quantified in terms of the mean flow contribution by the studies mentioned above and more recently by a comprehensive DNS study [6, 5], for the geometry used in this work a detailed investigation of the direct response of the separation bubble to the incoming disturbances has not been presented.

Low-Pressure Turbine Flow

The investigations in this work are based on data from direct numerical simulations that have previously been published [7, 6] and here only a summary of the general flow behavior is presented. The simulations have been conducted with an in-house CFD-code HiPSTAR. The numerical details can be found in the references above. A linear T106A blade cascade is simulated where the focus is on the midspan section such that a spanwise periodic domain can be considered. The blade-to-blade plane is illustrated in figure 1 and the spanwise extent is 20% of the blade chord length. The flow is entering from the lower left at an angle of 46 degrees with respect to the horizontal axis and exiting to the lower right. The Reynolds number, based on isentropic exit velocity, density and temperature as well as chord length, is 60,000 and the isentropic exit Mach number is 0.4.

Figure 1: TKE contours around the LPT blade - left: TU8, right: BAR. Red lines mark sampling regions.

Two cases are considered here to focus on the difference be-
between uniform and discrete disturbances. Uniform disturbances are created using a synthetic turbulence generation method at the inlet boundary that results in 3.8% turbulence level 30% chord lengths upstream of the leading edge and the case is referred to as TU8 in the following. Discrete disturbances are introduced by simulating an upstream bar moving with respect to the blade and this case is referred to as BAR. Using the bar passing frequency ($f_b$), the chord length $c$ and the isentropic exit velocity $v_{2n}$, the reduced frequency is defined as $f_r = f_b c / v_{2n}$, which for this case is 0.31. All quantities presented in the plots are nondimensionalized with inlet velocity, chord length, inlet density and inlet temperature.

For the following discussions results are sampled at three locations indicated by red lines in figure 1. The flow separates at $x \approx 0.6$. Hence, the first position is chosen to be upstream of the separation point, the second location in the area where KH rollers appear and the last location is at the trailing edge.

**Results**

Figure 2 highlights the differences between the two cases that will be discussed in the following. For the TU8 case we find a relatively clear shedding of vortices that are a consequence of the Kelvin–Helmholtz instability of the separated shear layer. These vortices - from now on denoted as KH-rollers for brevity - are shed periodically and show a strong spanwise coherence. However, the spanwise homogeneity of the KH rollers is broken due to the interaction of the rollers with the incoming turbulence. In the BAR case we find a strong intermittency due to the incoming wakes entering the passage and interacting with the mechanisms present in the TU8 case. When an upstream wake passes the separation region the turbulent fluctuations in the incoming wakes dominate the flow behavior. The clear shedding of KH-rollers seen in the TU8 case is suppressed by the strong mixing resulting from the passing of the wake. This leads to a vanishing separation bubble, and, hence, to the disappearance of the Kelvin–Helmholtz instability [6]. Interestingly, we find that in-between two passing wakes the shedding mechanism appears to recover. This agrees with the phase averaged result that have been presented of the same dataset [6]. In the present illustration we see that the existence of the separation zone is long and strong enough to develop a Kelvin–Helmholtz instability and the associated KH-rollers. For both cases, TU8 and BAR, we find that the KH-rollers always generate a coinciding footprint with negative skin-friction on the blade, whereas regions of positive skin-friction are located between two KH-rollers. This suggests that the unsteady nature of the shedding has a clear connection to the wall.

**Existence and Recovery of Kelvin–Helmholtz Shedding**

The auto-correlations of the pressure at different locations on the blade surface was calculated for a quantitative investigation of the coupling mechanism (figure 3). We find that for the TU8 case the time signal of the spanwise mean value of the second velocity gradient invariant $Q$ ($Q$ is chosen as representation of the KH-rollers) in the shedding region of the KH-rollers shows a clear periodic behavior. The period can be extracted from the auto-correlation to be approximately $0.165 (\Delta t \approx 0.33)$ and coincides with our visual impression of the flow data. The pressure data at the trailing edge shows a similar behavior but slight variations indicate the presence of a second, less dominant mechanism. This is believed to be caused by a second vortex shedding frequency intrinsic to the trailing edge shedding. The auto-correlations at the locations upstream and within the bubble, however, show a different behavior that can be explained as an upstream effect of the trailing edge vortex shedding [3]. The present correlations suggest that there is a superposition of the local pressure footprint of the KH-rollers superimposed by the signal resulting from the trailing edge shedding.

As previously shown with instantaneous snapshots (figure 2) the wakes generated by the bars are the most dominant mechanism in the BAR case and they are clearly visible in the auto-correlations (figure 3). Whereas for the upstream location only the passing wakes are clearly distinguishable in the auto-correlations, all other locations show a superposition with other mechanisms. For the signal of the velocity gradient invariant and the wall-pressure at the bubble location it is unclear which other mechanisms are superimposed with the wake events. However, the auto-correlation of pressure at the trailing edge in the time frame between two passing wakes shows strong similarity to the behavior in the TU8 case. This suggests that the Kelvin–Helmholtz shedding described for the TU8 case occurs between two passing wakes. In addition to the previous instantaneous impressions we find from the auto-correlations that the Kelvin–Helmholtz mechanism recovers relatively quickly after a wake has passed. When the wake passes the instantaneous velocity profiles are changed such that the KH-instability mechanism at the bubble location is not strong enough compared to the turbulence of the passing wakes, or vanishes altogether, and therefore is not represented by the auto-correlations. Towards the trailing edge the KH-rollers and their effect gain relative strength and develop a stronger overall influence.

The cross-correlations in figure 4 show how the different locations are coupled in terms of pressure. For the TU8 case all cross-correlations have their global extrema at negative $\tau$, indicating a strong upstream coupling of pressure which agrees with the work of [3]. For the BAR case the incoming wakes are the most dominant mechanism, reflected by the high levels of cross-correlation. The coupling of upstream pressure with both pressure in the separated region as well as at the trailing edge show only the coupling via the passing wakes. Contrasting this are the secondary peaks in the cross-correlation of wall-pressure at the trailing edge that indicate that the recovery of the Kelvin–Helmholtz mechanism in-between two passing wakes is strong enough to regain a strong coupling between the trailing edge and the separation bubble.

**Dependencies of the Separation Point Location**

The cross-correlations for the separation point location with other quantities is shown in figure 5 to analyze how the separation location is coupled with other mechanisms that govern the flow on the turbine blade. To that end a time series of the most upstream location at which the flow separates for the respective instance in time was sampled for each spanwise plane. The fluctuations around the mean separation point were then correlated with the second velocity gradient invariant $Q$ at a location above the separated region to identify the coupling between separation location and the Kelvin–Helmholtz shedding. Further, the separation location was correlated with the trailing edge pressure signal to identify the coupling with the trailing edge vortex shedding. For the TU8 case we find the global extrema for both correlations at negative time shifts. This indicates that for both couplings, separation location with KH-rollers and separation location with trailing edge vortex shedding, the upstream effects dominate over the downstream effects. In general both correlations show a certain degree of similarity in shape, but the correlation with the trailing edge is shifted towards positive $\tau$ compared to the correlation with the KH-rollers. These results indicate that the separation location is dominated by the vortex shedding cycle at the trailing edge, which by itself is dictated by the KH-shedding upstream. Hence the shift in $\tau$ between both
Figure 2: Skin-friction and vortical structures ($\lambda_{ci}$-criterion) are shown in the separation region on the suction side of the turbine blade (grey). Instantaneous contours of skin-friction shown from negative levels in red to positive levels in blue. Zero crossings of the skin-friction are highlighted as white lines. Vortical structures shown using $\lambda_{ci} = 8$. Left pair shows case TU8, the centre pair shows case BAR at a time instance when the incoming wake is passing and the right pair shows case BAR at a time instance between two incoming wakes passing.

Figure 3: Auto-correlations of the spanwise averaged wall-pressure signal at an upstream location ($p_{up}$), in the separation bubble ($p_{B}$) and at the trailing edge ($p_{TE}$) and the spanwise averaged value of the second velocity gradient invariant $Q$ in the shedding region of the KH-rollers ($Q_{B}$). Left: TU8, right: BAR. All locations are highlighted in figure 1.

In the BAR case this effect is annihilated and the upstream directed coupling between trailing edge and separation point location is destroyed by the dominance of the strongly intermittent incoming turbulence.

Coupling of Kelvin–Helmholtz Rollers with the Blade

The visualization shown in figure 1 already indicated that there is a coupling between the vortical structures above the wall and the wall itself. To investigate this coupling further figure 6 shows the cross-correlation of the pressure at one point at the wall in the separation region with the value of the second velocity gradient invariant $Q$ in the region above. The unconditional cross-correlation for the TU8 case has a negative peak at slightly less than 0.02 non-dimensional units above the wall. The location of this peak is close to the location of the inflection point of the velocity profile at this chordwise location, which is the origin of the KH instability. To understand the physics of this correlation the results are conditioned with high- and low-pressure events at the wall, respectively. The condition on high-pressure events weakens the peak of the correlation whereas an extremely strong peak is found for the low-pressure events. This indicates that the KH-rollers have a strong footprint at the wall in form of a low pressure region. Further the KH-rollers appear to develop a shear layer close to the wall as indicated by the slight overshoot of the correlation conditioned for low-pressure events when approaching the wall.

For the BAR case the correlation peak is found much closer to the wall. Here the extremum location does not coincide with the inflection point of the overall velocity profile at this chordwise location. However, it is close to the location of the inflection point of the velocity profile averaged only over the phase when the measurement location is in-between two wakes. In contrast to the TU8 case we find a strong near-wall shear layer coinciding with high pressure events. However, we find a similar footprint of vortical structures for the BAR case as was the case in the TU8 case. Here the pressure footprint of the KH rollers seems to be weaker, but the associated shear-layer appears to be stronger. Due to the additional fluctuations caused by the strong vortical structures of the incoming wakes, we have not been able to distinguish between the mechanism of the KH-rollers and the mechanism taking place during a wake passage. Nevertheless,
the results seem to indicate that a similar coupling of KH-rollers and the surface pressure is present in both cases.

Conclusions

The coupling mechanism between the upstream turbulence, the separation bubble and the trailing edge has been analyzed in two flows over the same low-pressure turbine blade. The incoming turbulence for the first case is homogeneous whereas for the second case strongly intermittent turbulence in form of distinct wakes enters the blade row of the turbine. The vortex shedding that develops due to the Kelvin–Helmholtz instability of the separation bubble is suppressed by the strong turbulence of a passing wake. This is believed to be caused by the strong mixing effect of the incoming wake that weakens the shear-layer and annihilates the instability. However, we found a relatively quick recovery of the incoming wake that weakens the shear-layer and annihilates the instability. For the homogeneous inflow turbulence the separation point location shows a dependence on the trailing edge vortex shedding which by itself is dictated by the upstream shedding of Kelvin–Helmholtz rollers. However, intermittent incoming turbulent wakes outmatch this coupling. No upstream effect of a trailing edge mechanism is recovered in this case.

A strong coupling of the Kelvin–Helmholtz rollers with the blade surface has been identified for the case with homogeneous inflow turbulence. The pressure minima located in the rollers’ cores reach down to the wall where they create local pressure minima in the surface pressure. Further, the Kelvin–Helmholtz rollers are associated with a shear-layer between roller and blade. The strongest correlation of wall-pressure with the rollers is found at the height of the inflection point of the mean velocity profile. For the case with incoming wakes the mechanism is modified and it has not yet been possible to draw robust conclusions other than the location of events that couple the flow with the wall-pressure. In this case the strongest correlation is located closer to the wall than in the case with homogeneous inflow turbulence.

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References


