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THE ROLE OF STREAMWISE VORTICITY IN FLOWS OVER TURBOMACHINE BLADE SUCTION SURFACES

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ABSTRACT

Streamwise streaks and vortices are frequently encountered in low Reynolds number flows over blading. Observations have shown that, in addition to flows over concave pressure surfaces, convex suction surfaces are also influenced by streamwise vortices. These observations are based on surface flow visualization studies and computational work with highly resolved Large Eddy Simulation. Fine scale organized streaks exist in the laminar regions of turbine and compressor blading and are predictable. For a turbine blade with a blunt leading edge, at Reynolds numbers typical of aircraft cruise conditions, the streamwise vorticity may persist, on a time-average basis, to influence the entire suction surface. Time resolution is required to capture the flow complexity that is fundamental for an understanding of the physical behavior of the laminar boundary layer and its separation and transition. Progress has been made in modeling and predicting transition and laminar separation and the new findings of interesting vortical behavior need to be incorporated. In the leading edge region spanwise vorticity may promote early transition and bubble closure; further downstream streamwise vorticity may become established. The physics of this streamwise vorticity imposes severe requirements on the temporal and spatial resolution of both experimental and computational methods. A narrow spanwise computational strip does not allow the streamwise vorticity to settle into an organized pattern; if it is to become organized, an adequate spanwise domain is required.

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INTRODUCTION

Turbine blade designers are quite familiar with the phenomenon of Görtler vorticity, which was thought to occur predominantly on the concave pressure surfaces of turbine blades. This organized system of vortices tends to increase heat transfer to the blade surface and also makes the flow and heat transfer very difficult to predict. In this context, the word “organized” is taken to be synonymous with “assembled”, “coordinated” or “structured” and carries no imputation of a responsible agent. Organization will be considered to be present if a structure persists on a time-average basis. It had generally been assumed that streamwise vorticity of this kind was confined to concave pressure surfaces. Examples will be given which should result in a questioning of that assumption. For a predominantly convex surface, this behavior may be unfamiliar but would be in accordance with the later predictions of Görtler [1], who postulated instability on a convex surface from the concave streamlines ahead of the leading edge stagnation region, with a resulting upstream zone of flow turbulence and subsequent inflectional instability.

In 1970 Kestin and Wood [2] published a theory predicting the spanwise wavelengths for streamwise vortices on a circular cylinder. “Streaky structures” and streamwise vortices have been observed and predicted on a wide range of bodies. On flat plates free-stream turbulence provides the stimulus [3]. They have also been observed on compressor blades [4, 5] and on the convex surface of a supercritical airfoil, following an initial concave surface exhibiting Görtler vorticity [6].

At high positive and negative incidence angles blades are prone to flow separation in the leading edge region. Any streamwise vorticity present might be expected to affect the separation behavior. This would then have an effect on the transition from laminar to turbulent flow.

The authors have observed streamwise vorticity on the suction surface of compressor and turbine blades, both experimentally [7] and computationally [8]. In this paper examples of this streamwise vorticity will be given. Implications of the behavior for laminar separation, boundary layer transition, and their prediction, will be discussed.

Results from Large Eddy Simulation (LES) [5] have demonstrated that instantaneous flow patterns in the leading edge region at off-design conditions can be complex. At low Reynolds numbers these flows can be predicted but enormous computing resource would be required to achieve this on a routine basis for design purposes. Time resolution is required to capture the vortical events that improve our understanding of the physical behavior fundamental for laminar boundary layers, laminar separation and transition. The computation also needs to be run for a sufficient duration that time averaging can take place for streamwise vortices to become organized. Wind tunnel studies have shown that organization may take upward of five minutes. The spanwise extent of the computational domain should be adequate to allow the vorticity to become organized; this may require the computation to extend to the end walls. This is also desirable if secondary and end wall flows are to be predicted. A narrow spanwise computational domain does not allow the streamwise vorticity to establish a regular pattern.

Lasheras *et al.* [9] concluded that plane shear layers are unstable to three-dimensional perturbations to upstream conditions. This instability results in the formation of organized, three-dimensional vortical structures that propagate and mutually interact under strain. This work was performed in the context of the strong spanwise vortices attending a free shear layer but the conditions are not too dissimilar from those in the leading edge region of a turbine blade.

Flows undergoing laminar separation, and possible reattachment, take many different forms. There are various classifications of laminar separation bubbles, and different candidates for the physical mechanism of the transition leading to bubble closure. Flows with incipient laminar separation will inherit the tendency to viscous instability, especially under the amplifying influence of an adverse pressure gradient and the viscous mechanisms of Tollmien-Schlichting (T-S) waves, which break down into turbulent spots. For thin laminar separation bubbles it may be anticipated that this mechanism will predominate. For thicker bubbles the inflectional influences on the Kelvin-Helmholtz (K-H) instability will become more aggressive resulting in transition and bubble closure. Furthermore the receptivity to external influences and by-pass mechanisms may intervene, resulting in an earlier and often relatively sudden transition. In the context of a separated flow this may result in the sudden collapse of a laminar separation bubble [5]. These mechanisms are strongly Reynolds number dependent so that a wide range of candidate scenarios is available.

The physical mechanism of boundary layer transition varies according to the level of pressure gradient sustained [10]. Whereas under zero pressure gradient conditions the behavior is quite stochastic, with random external influences largely determining the transition phenomenon and transition occurring in ‘sets’ or packets of T-S waves, under a strong adverse pressure gradient each wave participates in its own local transition process. This produces a transition region much shorter in length than under a zero pressure gradient but one which, nevertheless, is still very well represented by the universal intermittency distribution [11].

Streamwise vorticity is allowed for in a prediction method that takes account of the rapid merging of turbulent spots [12]. Laminar separation usually occurs as a result of strong adverse pressure gradients and predictions are needed that incorporate the appropriate transition physics. These considerations also prevail for attached flow transition. Because pressure gradients change rapidly any transition prediction procedure must be capable of adapting between transition modes. Any accurate treatment of laminar boundary layers at low Reynolds numbers has to be three-dimensional and have a sufficiently fine spanwise spacing to accurately resolve the streamwise vortical structures.

Questions of shear layer stability and transition to turbulence, of flow separation and stall, and the consideration of absolute and convective wake instabilities, can have a profound influence on the behavior of turbomachines. The periodic passage of wakes from upstream blade rows also affects transition and could cause its occurrence ahead of any laminar separation. Studies such as those of Halstead *et al.* [13] and Mayle [14] have documented this. Hughes and Walker [15] have used wavelet conditioning to identify instability phenomena in periodic transitional flows on compressor blades. In these flows the transition process was found to be mainly of the natural growth type, rather than the bypass type.

NOMENCLATURE

D	=	Cylinder diameter
L_z	=	Spanwise extent
Re	=	Reynolds number
Tu	=	Free-stream turbulence level, %
c	=	Blade chord
n	=	Amplification factor in inception prediction
r	=	Distance from blade surface
x, y, z	=	Coordinate directions
λ	=	Spanwise wavelength of vortex pairs

FLOW VISUALIZATION AND STABILITY THEORY

Examples of streamwise vorticity appearing on the convex surfaces of blading have been observed both experimentally and computationally. In this paper the designations of streamwise vorticity and streaks are used interchangeably. The existence of vorticity is taken to be implicit, whilst still requiring further detailed experimental characterization.

The results of surface flow visualization on the suction surface of a turbine blade tested in the transonic planar cascade tunnel at the National Research Council of Canada (NRC) are presented in Fig. 1. The blade was covered with a sheet of self adhesive white vinyl; a mixture of linseed oil and powdered lampblack was applied in a very thin layer. After running for five minutes, the blade was removed and photographed.

The large numbers on the scale represent percentage axial chord. Suction surface flow visualization was performed at three speeds, displaying coherent streamwise vorticity extending to the trailing edge. Figure 1 represents a discharge Mach number of 1.16, following strong acceleration through the blade passage from an inlet Mach number of 0.118. In this case the shock impingement and separation regions were in the vicinity of 70% axial chord.

Coherent fine-scale streamwise vortices cover the entire surface. An average spanwise wavelength, λ, of 0.55 mm was measured from Fig. 1 and this value was used in the subsequent comparison. Once established, with a characteristic dimension of the order of the laminar boundary layer thickness, the streaks appear to retain that spanwise wavelength, often as far as the trailing edge.

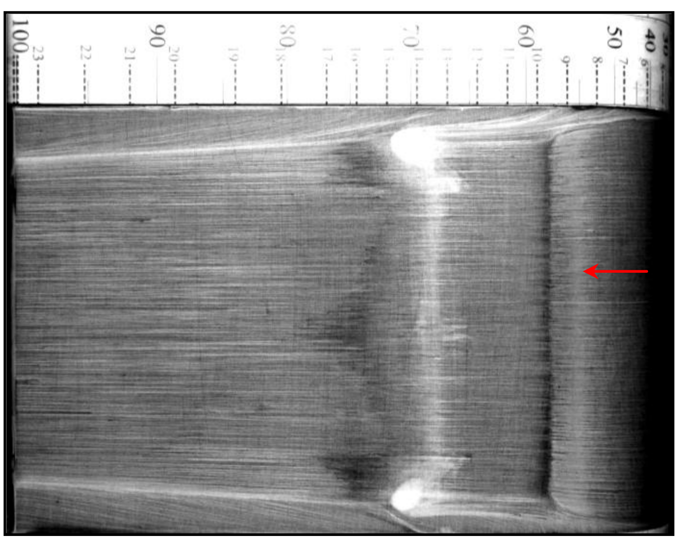

Figure 1. Suction Surface Flow Visualization at a Discharge Mach Number of 1.16.

Surface flow visualization photographs have been analyzed from a number of published experiments on blading. When examined in the same way as the surface flow visualization from the NRC cascade, two results from compressor blading (Schulz and Gallus [16], and Weber *et al.* [4]) and three further results from turbine blading (Benner *et al*. [17], Hodson and Dominy [18], and Halstead [19]) were accessible. Representative flow visualization photographs from all four turbine blade cases are given in Figs. 1-4.

Flow visualization was performed independently by different authors using different facilities. The techniques and materials used were different in each case. There exist cases in which two completely different visualization techniques have been used for the same model, giving an identical final result. This would seem to discount any suggestion that factors such as surface tension variations might influence the observations.

The results of Halstead were particularly useful as they covered a wide range of Reynolds numbers and free-stream turbulence levels. Results with boundary layer trips were also given. Turbulence levels above 4% and trips were not encompassed by the predictions [2]; visualizations of such cases were therefore not examined. A further very helpful feature of the Halstead experiments is that surface film gage signals were made available alongside the surface flow visualization. Features such as flow separation and re-laminarization were clearly indicated by the surface film traces. The streamwise streaks observed on the NRC cascade and on the cascade tested by Halstead were by no means confined to attached laminar layers. Figure 3 gives results from a turbine blade in the cascade tested by Hodson and Dominy [18]. Streaks in this case appear to be limited to the laminar boundary layer. This also appears to be the case in the visualization of Benner [17] (Fig. 4). All four examples exhibit

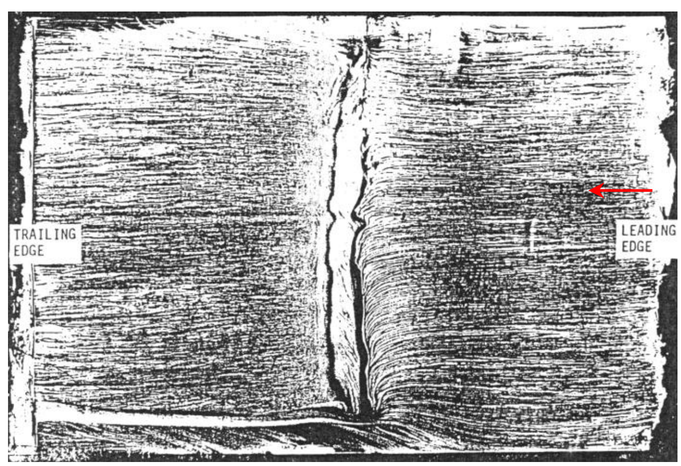

Figure 2. Suction Surface Flow Visualization of Turbine Blade by Halstead [19].

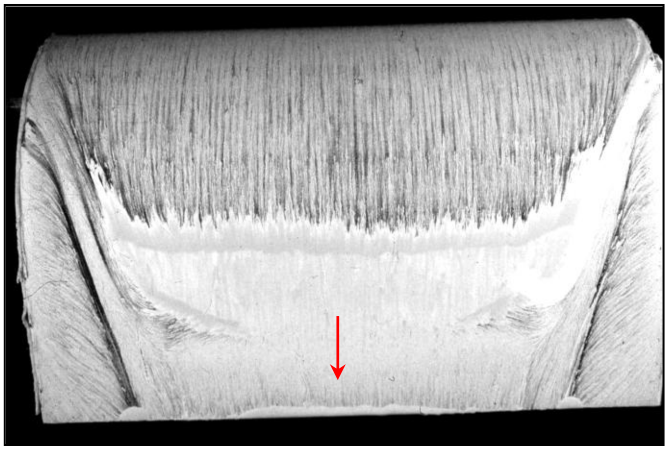

Figure 3. Suction Surface Flow Visualization of Turbine Blade by Hodson and Dominy [18].

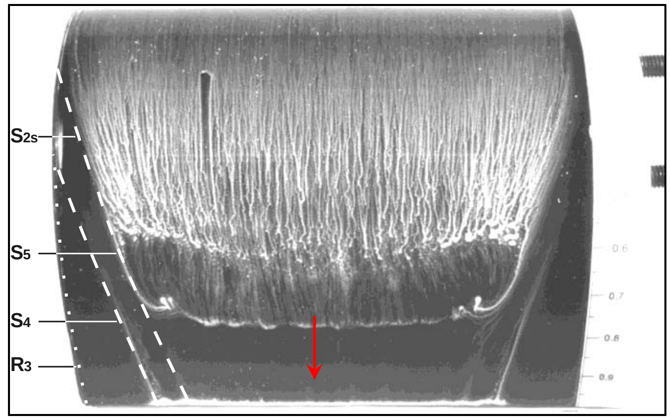

Figure 4. Suction Surface Flow Visualization of Turbine Blade by Benner *et al*. [17].

similar overall features of laminar separation and strong secondary vorticity. Figure 4 has the interesting feature of a horseshoe or scarf vortex emanating from a small surface excrescence.

For a predominantly convex surface the presence of streamwise vortices is unexpected but is consistent with the 1955 predictions of Görtler [1], who postulated instability on a convex surface from the concave streamlines ahead of the leading edge stagnation region. In 1970 Kestin and Wood [2] published a stability analysis of the flow around a circular cylinder. They predicted a theoretical value of pitch wavelength between vortex pairs, λ, for a circular cylinder of diameter, D, given by:

$$\lambda = 1.79\pi\, D\, Re^{-0.5}. \qquad (1)$$

This result (Eq. 1) is represented by the Tu = 0% line in Fig. 5. Kestin and Wood also undertook experimental work on circular cylinders which additionally provided the results for free-stream turbulence levels up to 4%.

It is difficult to locate turbine blade cases on the Kestin and Wood graph that was derived for a circular cylinder. The leading edge of many turbine blades is virtually circular; subsequently much of the suction surface retains a strong convex curvature over the forward portion and is quite flat further downstream. The rapid changes in curvature of the convex surface raise the question of what effective diameter should be applied if comparing with the Kestin and Wood model. Studies of the wall flow visualization and passage geometry for the NRC blade resulted in the conclusion that the blade surface curvature at around the 10% true chord location was quite representative of the curvature of streamlines approaching the suction surface. The measured spanwise wavelength for this blade was 0.55mm.

According to the theory this is compatible with the surface curvature on the suction surface at around the 10% true chord location. Although this is somewhat arbitrary it was found that if this was taken as a reference for turbomachinery blades then good and consistent agreement with the theory was obtained for all blades examined. With this significant assumption, the diameter of the osculating circle, at the 10% true chord location on the suction surface, was taken as the value of D, when comparing with the Kestin and Wood theory.

The measurements of the spanwise wavelength of the array of vortices are compared with the predictions of Kestin and Wood in Fig. 5. The four turbine blade cases shown above and the two compressor cases all gave reasonable agreement with the theory and experiments of Kestin and Wood. Free-stream turbulence levels for the cases analyzed were all in the range $0.2\% \leq Tu \leq 4.0\%$.

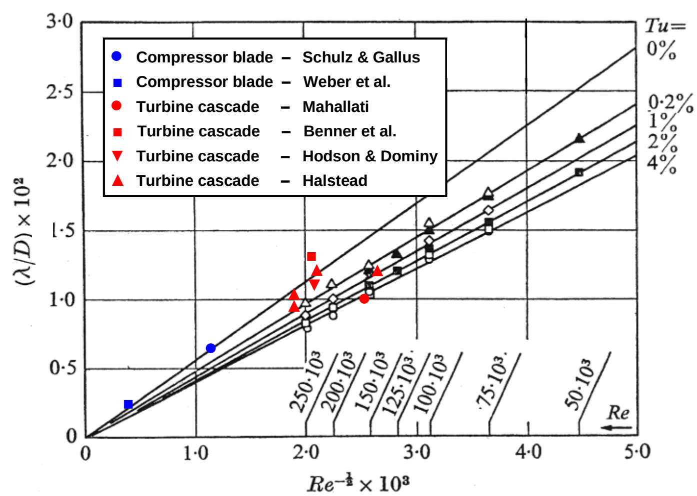

Figure 5. Measurements of Wavelength and Comparison with Kestin and Wood Predictions [2].

One outcome of these investigations is to establish that organized streamwise vorticity may occur more frequently on convex surfaces, such as turbine blade suction surfaces, than was previously appreciated. Investigations and predictions of flow behavior should be extended to address this possibility. These organized vortical structures could have significant implications for turbine aerodynamic and blade cooling design.

NUMERICAL INVESTIGATIONS

The advance of modern supercomputing power has permitted the numerical simulation of flows relevant to turbomachinery in recent years. Conventional RANS methodologies, commonly used in industry, produce an ensemble-averaged flow field and are incapable of resolving the near-wall structure in the flow. Similarly, hybrid RANS/LES methods utilize a RANS model in the boundary layer, and are also unable to resolve the structure in this region. It is through LES and Direct Numerical Simulation (DNS) that advances in our understanding of streamwise vorticity in boundary layers have been made in the past 10-15 years. As the near-wall resolution of DNS and LES must be similar in order to produce reliable results, both simulation types are discussed interchangeably in this section.

A comprehensive review of the early work on the simulation of natural transition in wall-bounded flows can be found in Kleiser and Zang [20]. Due to the high computational cost involved in DNS and LES, many early studies into boundary layer flows were performed in simple flow configurations. In recent years the simulation of realistic blade geometries has been feasible. Owing to the high computational cost of DNS/LES, the blades considered have been assumed periodic in the spanwise direction, with the blades being two-dimensional in nature. The majority of research has been performed on low-pressure turbine blades, as the low Reynolds number allows the complete flow to be simulated at a relatively low computational cost.

Whilst streaks in boundary layer flow have commonly been observed in LES and DNS studies of the turbulent flow, their presence in the laminar flow has come to light more recently. In flat plate boundary layers, the presence of streaks in the laminar flow is often promoted through the inclusion of continuous modes, which interact with the discrete T-S instability to promote transition in the boundary layer. It has also been shown that background turbulence in the free-stream can modify the transition process [21].

In turbomachinery flows, streaks in the laminar boundary layer have been observed on the pressure surface of both turbine and compressor blades [22, 23 and 8]. On the turbine blade these are attributed to the passage of incoming wakes over the blade surface, producing Klebanoff modes in the boundary layer. In the compressor blade simulation, where there are no incoming wakes, the formation of streaks is a result of Görtler vorticity on the concave pressure surface. On the suction surface of turbomachinery blades, streaks in the laminar boundary have been observed in LES of a low pressure turbine blade [22]. These streaks extend from the leading edge up to the point of separation, and have a markedly similar appearance to experimental flow visualization. The formation of streaks in the laminar boundary layer has been the subject of intense numerical research in recent years. As was described above, flat plate laminar boundary layers exhibit streaks when the flow is subjected to free-stream turbulence. These streaks are attributed to Klebanoff modes. For flows in more realistic geometries, such as circular cylinders or blades with a blunt leading edge, the interaction of the onset flow with the curved solid body also produces streamwise vorticity in the flow. These streaks have been observed in numerical simulations of idealized bodies with a blunt leading edge [24, 25], high pressure turbine blades [26], low pressure turbine blades [27], compressor flows [5], and circular cylinder flows [28]. In all cases the streaks wrap around the leading edge of the body and extend quite far downstream in the boundary layers on both sides of the solid geometry. These streaks are attributed to the interaction of the leading edge of the body with the background turbulence fluctuations.

In all of the above cases turbulence fluctuations were present in the onset flow, in the form of either free-stream turbulence or turbulence embedded within periodically passing wakes. Theoretical studies suggest that the stretching of vortex lines around the leading edge leads to the generation of streamwise vorticity at the plate surface [29]. It is not currently clear, however, how this generation technique relates to the substantial increase in streamwise velocity fluctuation in the stagnation region upstream of the leading edge of the solid body, observed both experimentally [30, 31] and in simulations [25, 5].

A plot of turbulence intensity along the stagnation streamline in the McMullan and Page simulation [32] is shown in Fig. 6. The fluctuation level rises dramatically at approximately 0.035c upstream of the leading edge, with a peak in turbulence intensity of about 40% recorded 0.02c upstream of the leading edge. The level then falls towards zero as the solid surface is reached. Similar behavior was observed from investigations by Perkins *et al*. [33] who, following Hobson *et al.* [30], emphasized the importance of anisotropic variations of turbulence in the leading edge region of a compressor blade. Computational work by Pook and Watmuff [34] demonstrated the generation of strong streamwise vorticity in a Blasius boundary layer when normal vorticity passes through an upstream contraction.

In the McMullan and Page study, this behavior was recorded in a simulation of a compressor cascade of Reynolds number 700,000 performed at an extreme negative incidence angle.

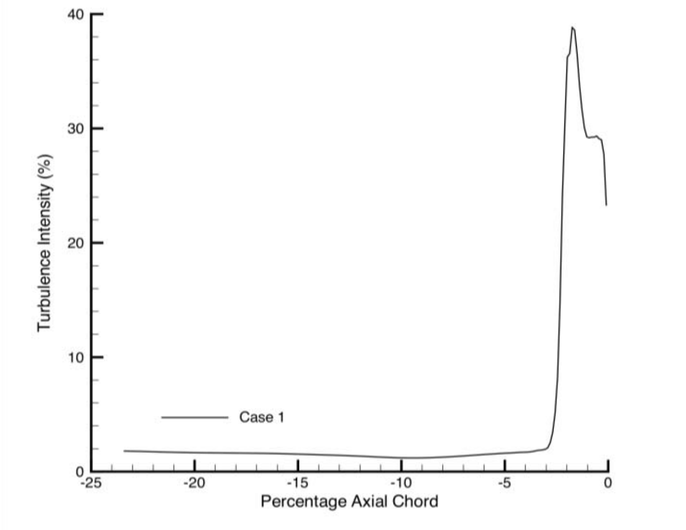

Figure 6: Turbulence intensity along the stagnation streamline upstream of the leading edge of the McMullan and Page simulation [32].

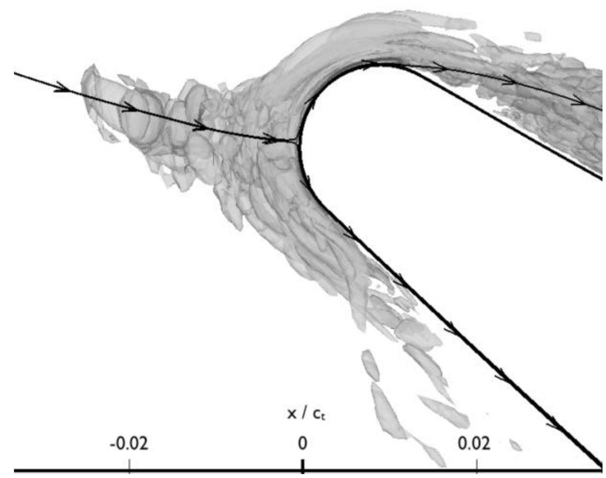

Figure 7. Iso-surface of Q-criterion showing formation of vortices in the stagnation region upstream of the leading edge of a compressor cascade blade. Re = 700,000

The span of the computational domain was set to 20% of chord. Background fluctuations were crudely modeled using white noise fluctuations of 1.4%, comparable to that found in the experimental setup. The Q-criterion was calculated from the vorticity magnitude and mean rate of strain to identify regions of flow where rotation dominates strain. In Figs. 7-9 iso-surfaces of Q-criterion [35] are shown. Figure 7 is an elevation view of vortical structures and of the mean stagnation streamline. The shading of the structures is slightly transparent so this view could be considered a spanwise-averaged representation. It is clear that strong vorticity is present on the stagnation streamline ahead of the leading edge and is at a maximum where the turbulence intensity indicated in Fig. 6 is at a maximum. Careful study of the toroidal structures suggests that they do not emanate from the blade surface but rather form upstream in a plane normal to the main stagnation streamline (Fig. 7). The most plausible explanation is that the observed turbulence along the stagnation streamline results from the formation and lateral movement of vortical structures ahead of the leading edge, in much the same way as observed experimentally by van de Wall *et al.* [31].

It can be seen in Figs. 8 and 9 that small, toroidal-shaped structures appear in the plane of the stagnation streamline, some 2% of chord upstream of the leading edge of the stator blade. When a sequence of these images is analyzed, it is observed that these strongly vortical toroidal structures aperiodically peel off in the stagnation region, their vorticity forming contra-rotating longitudinal structures as they are stretched onto the blade in the leading edge region. The formation of these toroidal structures upstream of the blade leading edge, and their subsequent transient behavior, provides an explanation for the dramatic increase in turbulence intensity demonstrated in Fig. 6.

Once the toroidal vortices shed from the stagnation region, they are stretched over the leading edge and form streaks near to the blade surface. These streaks enter the boundary layer from the free stream and extend far downstream of the leading edge on both blade surfaces.

The upstream toroidal structures are not turbulent but they and the subsequent streaks do display transient behavior, in that their spanwise position is not fixed. Both the McMullan and

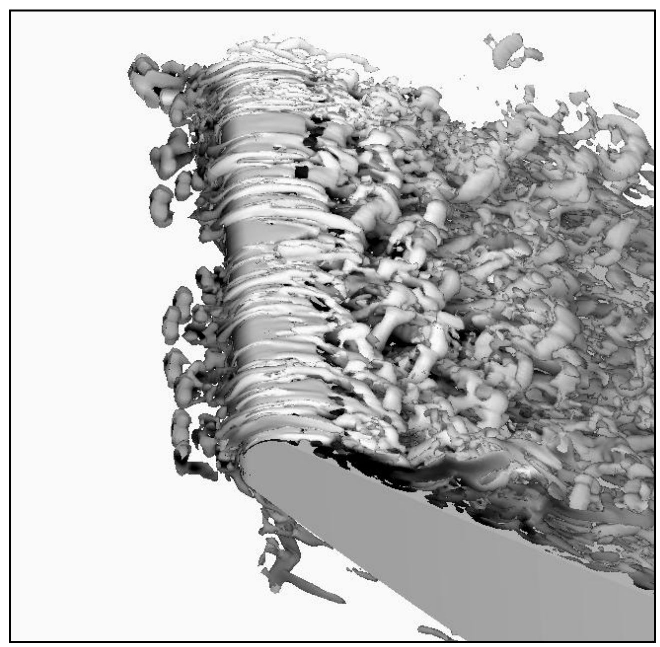

Figure 8: Iso-surface of Q-criterion showing formation of vortices in the stagnation region upstream of the leading edge of a compressor cascade blade. Re = 700,000

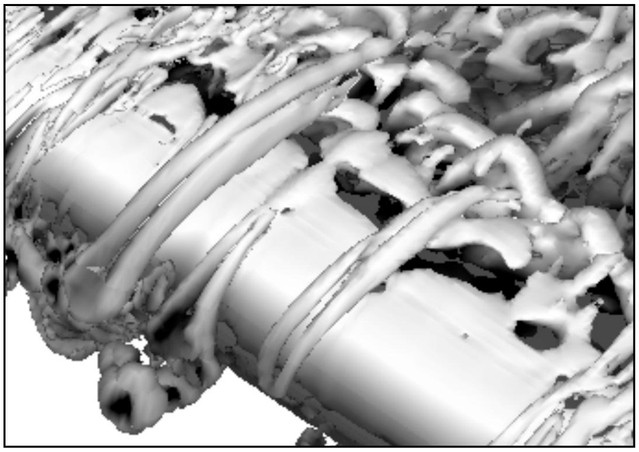

Figure 9: Iso-surface of Q-criterion showing vortex formation in the stagnation region and 'peeling off' into contra-rotating streamwise vortices.

Page [5] and Xiong and Lele [25] simulations report that the position of the streaks can change significantly over time. It is quite likely that in hot wire or Laser Doppler measurements their behavior could be interpreted as turbulent. In that case more careful frequency domain interpretation would be in order. It might also be expected that, in numerical flow visualization at least, a temporally-averaged representation of the flow would yield no direct evidence of their existence. This appears to contradict the evidence from oil-flow visualization of experimental data outlined in the previous section, where streaks are observed in flow visualization and acquire organization over significant periods of time (in excess of five minutes). Producing an averaged flow field of a DNS or LES of a realistic flow configuration over such a long time interval is currently beyond the capabilities of modern supercomputing, hence producing simulation data to quantify the experimental flow data remains a topic for future research. What is clear, however, is that streamwise vorticity is a common phenomenon on both the convex and concave surfaces of turbomachinery blades, and that understanding its origins and effects on the flow is of great importance if more efficient blade designs are to be obtained.

Conventional RANS modeling of linear cascades is performed using streamtube representations of the geometry of interest. It is common in such modeling to view the computational domain as a "thin-slice" representation of the full blade, with the span of the computational domain typically being only a few percent of the chord length. Given that wall-bounded LES requires a very high resolution near the wall to produce reasonable results ($y^+ \sim 1$, $x^+ \sim 20$, $z^+ \sim 20$), one approach to reducing the computational cost of the simulation is to restrict the span of the domain to a few percent of chord.

Whilst superficially attractive, the imposition of a narrow spanwise domain has been shown to significantly restrict

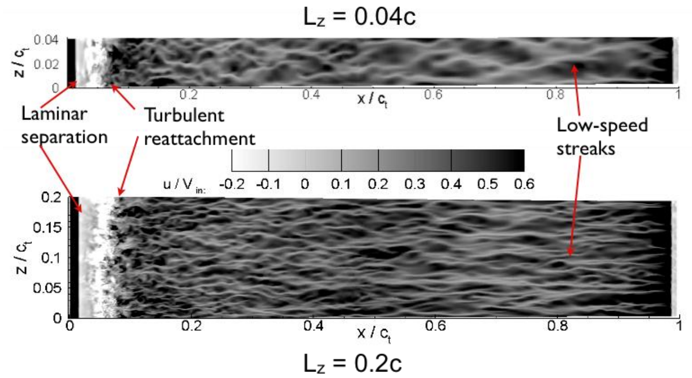

Figure 10: Contours of global axial velocity near to the suction surface of a compressor blade at an incidence angle of 45.96°. Top: Narrow span simulation. Bottom, Wide-span simulation.

boundary layer development [8]. This effect can be seen in Fig. 10, where the global axial velocity at a distance of $r/c = 8.9\text{x}10^{-4}$ from the suction surface is shown from a simulation with a high positive incidence angle. With a span of $L_z = 0.04c$, very few streaks are observed in the boundary layer, whilst a simulation with a span of $L_z = 0.2c$ displays a well-defined set of streaks with a regular distribution across the span. The predictions of the loss computed from the McMullan and Page [8] simulations show that the parasitic influence of the narrow span renders it extremely difficult to obtain an accurate prediction of the loss from the blade when a narrow domain is employed. In addition, the toroidal structures observed in the above simulation are not recorded in a simulation performed at matching conditions when a narrow span is used. It is clear, therefore, that future simulations of both "thin-slice" representations of linear cascades, and simulations of full blades, must have sufficient grid resolution, adequate domain extent, and suitably posed boundary conditions in order to accurately recreate the flow physics encountered in real machines.

TRANSITION AND LAMINAR SEPARATION

Transition Onset

Transition onset is generally the outcome of competition between different instability modes. Laminar stability theory describes "natural" transition under low free-stream turbulence. The basis of this was originally confirmed by Schubauer and Klebanoff [36] and led to the e^n prediction method for transition onset. Integral boundary layer calculations have traditionally been used to predict transition onset with calculation of the laminar layer momentum thickness Reynolds number proceeding from the origin until some previously determined empirical correlation curve for transition commencement is intersected. Such a correlation was produced by Abu-Ghannam and Shaw [37] predicting transition inception on a flat plate over a range of pressure gradients and free-stream turbulence levels.

The method and location of free-stream turbulence measurements is an important issue. Due to the strong accelerations and decelerations experienced in turbomachine blading, the local value of free-stream turbulence at the transition onset location may differ greatly from that on the stagnation streamline, which may also differ from an average value over the upstream flow field. Currently used transition onset correlations involve data from several workers, who may have adopted different bases for defining free-stream turbulence values: The Abu-Ghannam and Shaw correlation, for example, used neither a local value at breakdown, nor some mean value over the region of unstable flow, but rather an average value of free-stream turbulence taken midway between the leading edge of their plate and the location in question.

The Transition Region

All transition models are empirical to some extent. Only DNS can predict the whole transition process without recourse to empirical data. DNS has shed great light on the detailed physics of transition in boundary layers and separated shear layers under both low and high free-stream turbulence conditions. Because it is so demanding of computer resources, however, it remains impractical for engineering calculations at engine-representative Reynolds numbers. LES computations can successfully predict quite detailed features of transitional flow, especially in separation bubbles where the K-H instability predominates. However they are not yet capable of predicting the whole transition process, especially in attached flows, and modeling is still needed at the sub-grid scales.

The authors have been working on improved transition length predictions, based on measurements of transition length under adverse pressure gradients in natural and by-pass transition [38], and of triggered turbulent spots. It was realized that spot characteristics for adverse pressure gradients could be quite different from those for zero or favorable pressure gradients.

In zero pressure gradient flows, and for low free-stream turbulence levels, transition occurs by the stochastic and intermittent appearance of turbulent spots. As the pressure gradient becomes more adverse the amplification of T-S waves becomes more pronounced and the flow is dominated by these increasingly periodic effects. This appreciation forms the basis of the Walker [10] model of adverse pressure gradient transition. The qualitative differences in transition between zero and adverse pressure gradients were explained in terms of the influence of pressure gradient on the breakdown mechanism. Whereas the stochastic zero pressure gradient breakdown occurs in sets of T-S waves, under an adverse pressure gradient a more continuous breakdown takes place on an equi-spaced spanwise array. These idealized spots, based on each T-S wave cycle, eventually coalesce to complete the transition process. Walker developed a model for predicting the minimum transition length in an adverse pressure gradient. Measurements of transition length were compared with the predictions of minimum transition length. Improved correlations of spot propagation parameters were later produced and used to give a revised expression for minimum transition length in a limiting adverse pressure gradient.

Comprehensive observations of transitional flow in zero and adverse pressure gradients were made over a wide range of free-stream turbulence levels [38]. Solomon *et al.* [12] subsequently developed methods to apply these results for predicting transition length in non-similar flows with arbitrary surface pressure variation in the transition region. This substantially modified the earlier model to allow for local variations in spot formation rate and of spot celerities and spreading angles as the pressure gradient is varied. This theory was successfully applied to improve predictions for low Reynolds number airfoils with laminar separation [39, 40]. The basic Walker transition length model was predicated on the assumption (based on available zero pressure gradient data) that the transitional flow length would be controlled by longitudinal spot merging because the spanwise spot merging occurred more rapidly. Spanwise spot merging occurs more rapidly under adverse pressure gradient conditions. The Walker model should therefore continue to be valid for that case; the same should be true where fine scale three-dimensionality is introduced by external agents. It could likewise be expected that the Solomon *et al.* [12] procedure would remain valid. The behavior of the streamwise vortices present over blade surfaces is fundamental to the transition processes in both attached and separated flows. The LES results of McMullan, typified by Figs, 8 and 9, lend support to the above interpretations of transition and especially its role in closing a laminar separation bubble. These computational results appear to be in accordance with the findings of Durbin *et al*. [41] on the importance of mode interaction.

Laminar Separation

Any blade surface boundary layer must eventually separate if subjected to a strong enough deceleration. Laminar separation bubbles can result from laminar separation followed by sufficiently early transition in the separated shear layer and subsequent turbulent reattachment. Errors in predicting the length of these bubbles have often led to the failure of design routines to give stable or accurate solutions. The length of a separation bubble is largely determined by transition and there have been a number of attempts to predict bubble closure, by predicting transition. Hatman and Wang [42], for example, have investigated "transitional separation" in which transition onset precedes separation.

Early attempts at describing separation bubble development and bursting, such as those of Horton [43] and Roberts [44] were based on semi-empirical models assuming a constant pressure over the separated laminar shear layer region, instantaneous transition, and a linear variation of free-stream velocity during turbulent reattachment. The authors are currently reviewing experimental, analytical and numerical studies of separated flow transition. The validity and limitations of engineering models for predicting transition in separated flow, with particular reference to axial turbomachine airfoils, are under consideration.

Several recent studies have highlighted the significant influence of streamwise vorticity on separated flow transition phenomena under the high free-stream turbulence conditions experienced by embedded blade rows in a multi-stage turbomachine. Filtering of disturbances from the free-stream produces streaky structures in the separated shear layer, similar to Klebanoff modes in attached boundary layers under a turbulent stream. Transition onset is then characterized by the appearance of vortex loops, or hairpin eddies, at a frequency related to the dominant K-H frequency of inviscid instability in the separated shear layer. This suggests that turbulent breakdown in a laminar separation bubble under these conditions occurs through interactions of T-S waves with streamwise structures having a much smaller spanwise length scale [41]. Under high free-stream turbulence conditions DNS studies show turbulent breakdown originating from K-H instability in the outer region of the boundary layer [45].

The streaks also significantly alter the characteristics of any laminar separation bubble that forms on the pressure surface, as the contra-rotating vortex pairs rapidly destroy the spanwise coherence of the K-H roller that forms on the separation bubble, and reduce the length over which the transition and bubble reattachment occurs. This is in contrast to the situation on the suction surface where a high positive incidence produces a typical leading edge bubble. The K-H roller is susceptible to a secondary instability which precipitates a transition to turbulence and subsequent reattachment.

There are a number of different mechanisms by which periodic spanwise disturbances might be introduced to separated flow regions on a turbomachine airfoil. The filtering of disturbances from a turbulent stream will be important regardless of the location of the separated flow region on the airfoil. The Kestin-Wood stagnation flow instability is relevant for turbine blades, which tend to have a blunt leading edge. Streamwise vorticity has also been observed in the suction surface laminar layers of compressor airfoils and is also relevant to the leading edge laminar separation bubbles that are commonly observed at off-design conditions. Spanwise periodicity on a turbine airfoil suction surface can also be introduced by the periodic impingement of wake jets arising from the relative motion of an adjacent upstream blade row; this produces a moving stagnation line that convects with the passing wake. The region of concave flow curvature at a separation point that is associated with deflection of the approaching boundary layer away from the surface is an additional candidate for invoking Görtler instability on compressor blades.

Regardless of the importance of these instability mechanisms in generating spanwise periodicity, it has recently been pointed out that a two-dimensional separation line is not topologically possible [46]. Similar arguments would require the existence of three-dimensionality, with associated spanwise periodicity and generation of streamwise vorticity, at an attachment line in the stagnation region of a two-dimensional stream.

DISCUSSION

At this stage the evidence for streamwise vorticity on the suction surface is strong but qualitative. This investigation is proving the usefulness of a combined approach of wind tunnel experimentation and computational work. The computational work has given fleeting glimpses of intense vortical activity especially in the leading edge region of blades. The toroidal structures encountered on the leading edge stagnation streamline arise very quickly and collapse as quickly into contra-rotating streamwise vortices on both pressure and suction surfaces of a blade. This is particularly marked when the blade is at an extreme of positive or negative incidence. The intense streamline curvature under these conditions seems to play a strong part in this, as it does on the bluntness and strong curvature of turbine blade surfaces. On sharper leading edges it is more likely to be the free-stream turbulence that excites the streamwise vorticity.

The toroidal vortex structures, and the ensuing contra-rotating streamwise vortices, are transitory and quite mobile in spanwise location. Therefore, during the relatively brief sampling possible with current computational capabilities, no long time-averaged or organized structure has yet been discovered in computed work. Having said this Fig. 10 shows that as the spanwise extent of the computed domain increases there is more of a tendency to stability and organization. The experimental flow visualization work has different characteristics and does not show the very rapid and transitory vortex structures. No systematic vortex structure is observed immediately but surface flow visualization after a five minute run shows ubiquitous fine scale vortex structure in the experiments of several authors. This time-averaged behavior does indicate organized vortex structure and streaks with energetic mixing between the free stream and the surface boundary layer. The streaks do not appear to be particularly dependent on the state of the boundary layer although they are more common in laminar layers. The relationship between the transient structures observed from computations and the steady state organized behavior from experiments is presently the subject of conjecture, but is not yet proven.

The physical mechanisms involved in the vortical behavior are still not perfectly clear. Toroidal vortices splatting on the leading edge could produce attached streamwise vortices. It is not yet clear where the toroidal vortices come from, and in which direction they are convecting. The instability and linking of closely-spaced, quasi-parallel vortex elements could be a factor. This is observed in boundary layer transition by Knapp and Roache [47], and also in the decay of aircraft wingtip vortices. The intense stretching of free-stream eddies around a leading edge could possibly lead to a similar situation, where linking of the legs would lead to ejection of a vortex ring. This could propagate upstream in the stagnation region, where the velocity is low, but might subsequently be entrained by higher velocity flow and convected back near the surface. The most likely situation for this to occur would be at high incidence (positive or negative) where the stretching of flow around the leading edge is most intense.

The development of streamwise vorticity is an essential stage in the transition from laminar to turbulent flow in both boundary layers and separated shear layers. In "natural transition" of two-dimensional boundary layers, a long period of amplification of two-dimensional disturbances is required before the resulting spanwise vorticity concentrations become unstable to three-dimensional disturbances, leading to the production of "lambda vortices" with predominantly streamwise legs. The long two-dimensional phase of natural transition can be "bypassed" through external agencies that introduce streamwise vorticity directly; well-known examples of bypass mechanisms include the development of Klebanoff modes in boundary layers under a turbulent free-stream, scarf vortices trailing from isolated surface roughness elements, and vortices generated by crossflow effects. Any bypass mechanism will accelerate the appearance of turbulent flow, and hence have a major influence on both laminar and turbulent separation phenomena and general airfoil performance characteristics.

The present paper discusses a new mechanism for generation of streamwise vorticity at the leading edge of an airfoil in a turbulent stream; this is particularly relevant to the flow around turbomachine airfoils that necessarily operate in the highly turbulent environment created by wakes of upstream blade rows. Both computational and experimental work suggest that, although the turbulence may originate in wakes or as free-stream turbulence, this is not essential. Strong curvature of impinging streamlines or the lateral motion of the stagnation streamline as it approaches the leading edge may also induce the streamwise vorticity. In addition to information on free-stream turbulence levels and length scales it may be important to also consider turbulence arising locally from events in the vicinity of the leading edge.

The next step will be to provide quantitative confirmation of the vortical nature of the streaks and evidence on the physical origin and development required to verify and validate computational modeling. An important aspect of the physical understanding of these structures is an appreciation of the effects of streamline curvature and increased disturbance levels in the leading edge stagnation region that is more localized than the application of an average upstream turbulence level. The implications for design should then be explored. It is anticipated that there could be implications for flow control, through more accurate application of devices of the riblet type, and for heat transfer, in providing information on localized predictions of increased heat transfer that could impinge on blade cooling strategies.

CONCLUSIONS

Fine scale organized and predictable streamwise vorticity has been shown to exist in the laminar regions of turbine and compressor blading. For a turbine blade with a blunt leading edge the streamwise vorticity may persist on a time-average basis to influence the entire suction surface at low Reynolds numbers typical of aircraft cruise conditions.

The flow over a circular cylinder was analyzed by Kestin and Wood but turbine blade leading edges have a different geometry with varying surface curvature. Exact predictions by the theory cannot therefore be expected; rather, behavioral similarities are sought. For comparisons with the Kestin and Wood theory an effective cylinder diameter was applied; this was taken to be the diameter of the osculating circle at 10% true blade chord. Consistent application of this criterion gave reasonable agreement between flow visualization and prediction for all blade geometries considered.

LES results demonstrated that instantaneous flow patterns in the leading edge region at off-design conditions can be very complex. Feeting glimpses were gained of intense vortical activity in the leading edge region. Toroidal structures were encountered on the stagnation streamline; they arose quickly and collapsed as quickly into contra-rotating streamwise vortices. The intense streamline curvature under high incidence conditions plays a strong part in this but on sharper leading edges it is more likely to be the free-stream turbulence that excites the streamwise vorticity. The streamwise vorticity may interact with spanwise vorticity in separation regions promoting early transition and bubble closure.

At low Reynolds numbers these complex leading edge flows can be predicted but they also emphasize the enormous computing resource required to achieve this on a routine basis for design purposes. The grid needs to be very highly resolved to minimize the dependence on sub-grid modeling. Time accuracy is required to capture vortical events required for an understanding of the physical behavior fundamental for laminar boundary layers, laminar separation and transition. The computation also needs to be run for a sufficient duration that time averaging can take place for streamwise vortices to become organized. For this to happen a further requirement is an adequate spanwise extent for the computational domain. This may require the computation to extend all the way to the end walls, which is also desirable if secondary and end-wall flows are to be predicted.

It is therefore clear that accurate modeling of the flow needs to address the issues raised by this streamwise vorticity and that a two-dimensional approach will be inadequate. This has been allowed for in a prediction method that takes account of the lateral merging of turbulent spots as well as their longitudinal merging. Prediction approaches are needed that incorporate the transition physics which occurs under the strong adverse pressure gradients conducive to laminar separation. These considerations also prevail for attached flow transition. Because pressure gradients change so rapidly any transition prediction procedure must be capable of adapting between modes. Any accurate treatment of laminar boundary layers at low Reynolds numbers should be performed three dimensionally and with a sufficiently fine spanwise spacing that streamwise vortical structures are resolved.

The outcome of these investigations is to establish that organized fine-scale streamwise vorticity may occur more frequently on convex surfaces, such as turbine blade suction surfaces, than hitherto appreciated. Experimental work, and computational predictions, should be extended to encompass that possibility. To the extent that the flow behavior described in this paper is widespread it will have implications for turbine blade aerodynamic and thermal design.

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