Stationary and Traveling Vortical Structures on Swept Cylinders and Turbine Blades

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Suction surface flow visualization on turbine blades at subsonic and transonic speeds showed robust streamwise streaks on a lengthy time-average basis. The normal flow past a circular cylinder is a more canonical case and testing was undertaken at high speeds on a 38 mm diameter cylinder and at low speeds on a 152 mm diameter cylinder. The lateral spacing between streaks on cylinders had been predicted by Kestin and Wood and the present tests gave excellent agreement with their theory. Although their work was related to unswept circular cylinders it also provides an excellent benchmark for sweep effects on cylinders and turbomachinery blading. The observations of streaks on turbine blades and unswept cylinders provided a firm basis for referencing the influence of sweep. Experiments on a circular cylinder were performed over a range of sweep angles from zero to 61^{o} giving results for lateral spacing and angular orientation of the streaks. At high-sweep angles the results are consistent with those of Poll. The introduction of sweep brings consideration of a wide range of instabilities; streamwise and crossflow structures are present on the suction surface of turbine blades. Although the available information on fine structures comes from surface flow visualization, work is now progressing on hot wire measurements away from the surface. The aim is to demonstrate the relationship between the structures and the surface traces. Analysis of the data is complemented by ongoing theoretical work. It is also hoped to provide information on the changing behavior of the vertical structures as the sweep angle is increased. The streamwise disturbance in the unswept case was found to be stationary in nature and to be resilient, often persisting from leading edge to trailing edge. Crossflow instability becomes more significant as sweep is increased. It grows aggressively and rapidly, being predominantly of a traveling nature, and has a major role to play in the transition process. The observed streaks could be of particular concern for the thermal design of turbine blades. It is hoped to give designers confidence about the flow regimes they might anticipate for a given sweep angle and particularly of when and how the aggressive crossflow instability mode is likely to be encountered.

Nomenclature

D	Cylinder diameter
Re	Reynolds number
Tu	Free-stream turbulence level, %
λ	Lateral spacing between vortex pairs
λ_o	Spacing between vortex pairs for unswept cylinder
Λ	Sweep angle, degrees

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I. Introduction

A highly loaded turbine nozzle vane was tested over a range of Mach numbers in a planar cascade at the National Research Council of Canada (NRC). Surface flow visualization by Mahallati, as reported by Gostelow *et al.* [1], indicated strong and persistent streamwise vortical structures on the convex suction surface, as shown by the representative visualization in Fig. 1. These streamwise streaks have been shown to be quite common on the suction surface of turbine blades resulting in an examination of the fundamental flow behavior causing the phenomenon. This observation instigated the present investigation. Fine scale organized and predictable streamwise vorticity has been shown to exist on both the pressure and suction surfaces of turbine blades. Resulting from the unstable concave streamline curvature over a blunt leading edge the streamwise vorticity may persist, on a time-average basis, to influence the entire suction surface at the modest Reynolds numbers typical of aircraft cruise conditions. The lateral distance between streaks is thought to be an indicator of the extent of the vortical activity from the surface. The vorticity is considered implicit, whilst still requiring detailed experimental, computational and analytical characterization.

Designers generally assume that streamwise vorticity of this kind is confined to concave pressure surfaces. The authors have observed streamwise vorticity on suction surfaces, both experimentally [1] and computationally [2]. In this paper examples of this streamwise vorticity on convex surfaces will be considered. This behavior had been predicted and observed previously in low speed flows, with attendant theories for wavelength. For a predominantly convex surface the behavior is consistent with the later predictions of Görtler [3], who postulated instability on a convex surface from the concave streamlines ahead of the leading edge stagnation region.

The spanwise wavelength of the array of fine-scale streamwise vortices had been predicted by Kestin and Wood[4]. The physics of this streamwise vorticity imposes severe requirements on the temporal and spatial resolutions of both experimental and computational methods. Temporal resolution is needed to capture the flow complexity that is fundamental for an understanding of the behavior of the laminar boundary layer and its separation and transition. However the vortical structures may be quite unstable, the stationary vortices only appearing in an organized fashion after extensive time-averaging. This combination of instantaneous and long duration mapping of any associated vorticity presents a strong challenge for both instrumentation and computational resources.

For any given flow regime various candidate instability modes exist. In unswept circular cylinders streamwise vorticity may be associated with a high local disturbance level upstream of the leading edge. This is then stretched

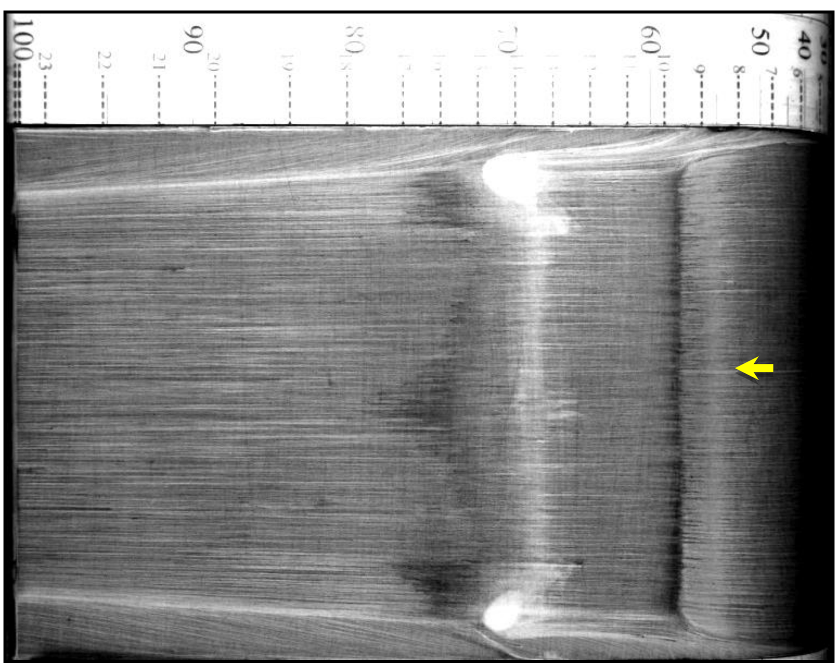

Figure 1. Suction Surface Flow Visualization of Turbine Blade at a Discharge Mach Number of 1.16 [1].

out into a lengthy vortical structure as it passes along the convex surface [5]. It may well comprise both weakly organized and meandering structures. After a relatively long time the stationary components settle into a clear time-averaged pattern. Halstead [6] has shown that the structures can persist through the turbulent boundary layer to the trailing edge. These fine-scale streaky structures may persist through shock interactions, laminar separation bubbles, the transition region and well into the turbulent layer [1]. Figure 2 gives an enlarged view of the vortical streaks towards the trailing edge of the turbine blade suction surface.

Kestin and Wood had demonstrated the existence of streamwise vortices on an unswept cylinder [5]. Poll went on to examine vortex behavior on a highly swept cylinder [7]. A gap has existed between the investigations of Kestin and Wood, at zero sweep, and those of Poll, with 55^{o} to 71^{o} of sweep. There had been no previous published attempt to link the experimental data sets of Kestin and Wood and of Poll and the aim of the present investigation is to bridge that gap. The Kestin and Wood theory may be regarded as the limiting case for zero sweep angle and it is of interest to work from that to consider stability over a wide range of sweep angles. It would be particularly reassuring to have experimental measurements to support the theoretical work and such a program of work is planned. A more recent and different approach was taken by Takagi *et al.* [8] for a sweep angle of 50^{o}.

Introducing sweep brings consideration of a wide range of instabilities. Prominent is crossflow instability resulting from the inflectional behavior of the three-dimensional boundary layer. Although there are substantial differences between streamwise vortices and crossflow vortices, it has never been clear how, and where, the streamwise vorticity changes to crossflow vorticity or what other instabilities are active. Nevertheless a gap in sweep of at least 50^{o} between the results has continued to exist. The authors considered it worthwhile and interesting to perform experiments over this unexplored region of parameter space.

The circular cylinder in crossflow is an important canonical case; for guiding the interpretation of the flow over more complex geometries, such as swept wings and turbine blades. Previous flow visualization investigations have often revealed streamwise vortices and “streaky structures” on flat plates. These were often ignored, considered to be an artifact of the flow visualization medium or of its application. For the cases addressed here, care was taken to eliminate the influence of the visualization medium and application by systematically varying these.

II. Experimental Facilities and Flow Visualization

The work on turbine blades and circular cylinders has drawn on a wide range of results, from different facilities, and covering a wide range of Reynolds and Mach numbers. Results are included from the testing of a 0.152 m diameter cylinder with and without sweep. Tests on the near-surface flow over this circular cylinder were conducted in the Charles Wilson wind tunnel at the University of Leicester. This is a closed-loop low speed tunnel with an aerodynamic working section 0.85 m high, 1.145 m wide, and 4 m long. A downstream fan feeds the return leg of

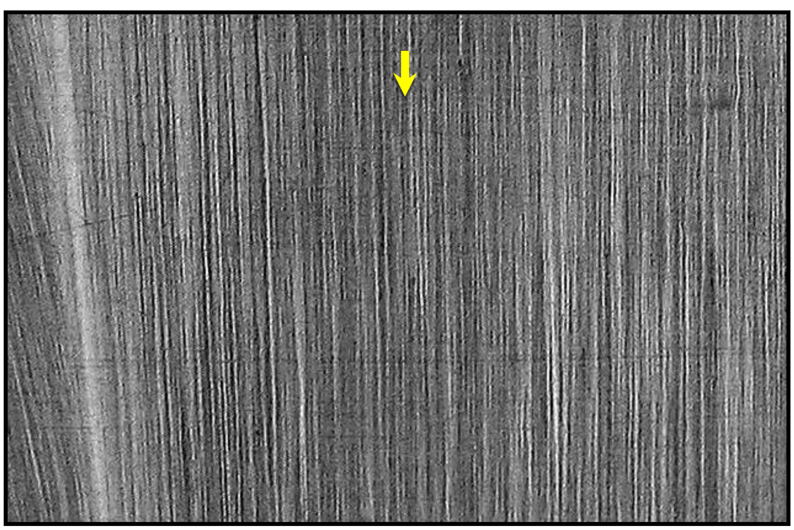

Figure 2. Suction Surface Flow Visualization between 80% and 95% Axial Chord of NRC Turbine Blade at a Discharge Mach Number of 1.16.

the wind tunnel circuit. The return flow is conditioned through three mesh screens and a honeycomb layer followed by a further screen upstream of the 4:1 area ratio converging test section inlet. This resulted in a free-stream turbulence level of 0.2% at 10 m/s.

The 0.152 m diameter, 2.5 m long, hollow aluminum cylinder was placed in the forward region of the test section. The cylinder was mounted 2.75*D* above the floor with its axis parallel to the wind tunnel floor; it was pin-mounted on the tunnel far-side wall and simply supported through the near-side wall. This arrangement allows the cylinder to be manually adjusted in fixed increments of sweep over the range 0^o to 61^o. At sweepback angles less than 61^o the cylinder protrudes outside the working section through tight-fit elliptical holes cut in the Perspex near-side wall. In the regime tested a cylindrical model would normally give rise to von Kármán vortex shedding. To suppress this instability the leeward side of the cylinder is fitted with an L-shaped aluminum splitter plate mounted from the rear stagnation line. The effectiveness of this suppression method was verified by hot-wire measurements in the cylinder wake. End plates were used to prevent the wind tunnel side wall boundary layer from interfering with the cylinder flow. The elliptical hole for the cylinder is located 10% mean chord upstream of the ellipse center to give stability in yaw. At zero sweepback, the cylinder length between the end plates is 1.079 m.

On the circular cylinder tested at Leicester University the windward surface was prepared for flow visualization by hand polishing the surface to a uniform reflective finish over the arc of -110^o to $+110^o$ about the upstream stagnation line. The leeward side, left unpolished, is characterized by separated flow. At the test section mid-span, a 0.4 m wide 0.226 mm thick sheet of UV stabilized clear PVC was tightly wrapped around the cylinder. The sheet was held in place by adhesive tape attached to the leeward side of the cylinder. The sheet created a removable surface over which a flow visualization compound was applied. Changing the sheet between tests built a library of flow records for subsequent analysis and comparison.

A sample of flow visualization on the suction surface of a turbine blade tested in the NRC transonic planar cascade tunnel was given in Fig. 1. The discharge Mach number was 1.16. 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. Flow visualization at subsonic and transonic speeds displayed coherent streamwise vorticity extending from leading to trailing edge. Some results from turbine cascades are presented in reference [2]. When examined in the same way as the surface flow visualization from the NRC cascade, three further results from turbine blading were accessible [6,9,10]. The visualization was performed independently by the different authors using different facilities. Techniques and materials used differed in each case, demonstrating that factors such as surface tension or gravity did not influence the observations.

Ackerman [11] performed surface flow visualization on a 37.26 mm diameter cylinder at a free stream Mach number of 0.5. Streamwise streaks were observed before and after a separation bubble. The application of the visualization medium upstream of separation had been non-uniform. Because the liquid medium collected in a pool in the bubble a more uniform dispersion of the medium was observed downstream of the bubble. Spanwise periodicity showed up clearly, forming a viable basis for measuring the spanwise wavelength (Fig. 3).

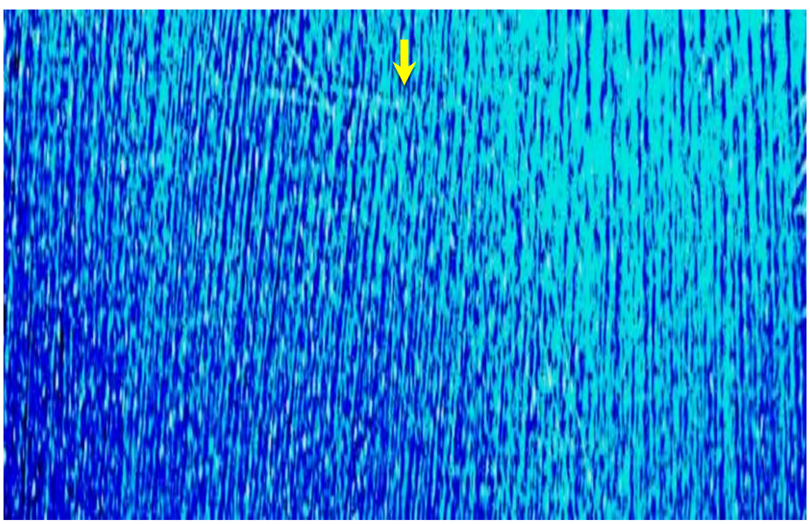

Figure 3. Surface Flow Visualization downstream of Separation Bubble on Circular Cylinder in NRC Tunnel at a Mach Number of 0.5.

Poll had considered that surface flow visualization was not feasible below the Reynolds numbers he had investigated. Since the Reynolds numbers used in the present investigation were well below those used by Poll it was not clear that streaks would be observed on the circular cylinder. This represented the biggest challenge for the investigation. Systematic experimentation was applied to this question and eventually a mixture was found that gave streaks consistently over the chosen Reynolds number range. This made flow visualization at low speeds possible. The flow visualization compound comprises a suspension of 1 g of desiccated titanium dioxide powder in a solution of 10 ml of paraffin oil, 0.84 ml linseed oil, and 3 drops of polyoxyethylene 10 oleoyl ether. Before each application, the cylinder span was wiped with linseed oil, using a soft cloth, to form a thin film that improved the dispersion of the compound. The compound was applied over the PVC sheet using a soft brush, stroking along the cylinder axis. After applying the mixture, the cylinder was tested by running the tunnel at a constant Reynolds number for about forty minutes. The surface flow visualization pattern on the removable plastic sheet was analyzed by removing the sheet from the cylinder, placing it on an overhead projector, and projecting the pattern together with a reference grid onto a large white screen. The magnification from the optical projection facilitated the measurement of the visualization traces on the screen.

III. Streamwise Vorticity

Circular Cylinders without Sweep - the Benchmark

The crossflow over a circular cylinder is a canonical problem and the existence of regular streaks on circular cylinders was originally investigated by Kestin and Wood [4] who, in 1970, published a stability analysis. They predicted a theoretical spanwise wavelength between vortex pairs, λ, for a cylinder of diameter, D, given by:

$$\lambda = 1.79\pi D Re^{-0.5}. \tag{1}$$

This result (Eq. 1) is represented by the Tu = 0% line in Fig. 2. Kestin and Wood also undertook experimental work on circular cylinders which provided the results for non-zero turbulence levels.

In order to confirm the suitability of the Kestin and Wood theory as a basis for examining more complex surface geometries, and variables such as sweep, further experimental work was undertaken on circular cylinders. In 2002 Ackerman [11] had performed surface flow visualization on a 37.26 mm diameter cylinder at a free stream Mach Number of 0.5. Streamwise streaks were observed before and after a separation bubble. Application of the visualization medium upstream of separation had been non-uniform. Because the liquid medium collected in a pool in the bubble a more uniform dispersion of the medium was observed downstream of the bubble. In this region spanwise periodicity showed up clearly (Fig. 3) and formed a viable basis for measuring the spanwise wavelength. This experiment was performed at the relatively high Reynolds number of 675,000 and provided a point for comparison with the Kestin and Wood prediction.

More recent testing was undertaken on the 0.152 m diameter aluminum cylinder in the University of Leicester low speed tunnel at three Reynolds numbers. Surface flow visualization has provided a further three points on the Kestin and Wood plot in Fig. 4. All four results are in reasonable agreement with the Kestin and Wood theory and provide confirmation of this theory for the case of the normal flow over an unswept circular cylinder. The suitability of the Kestin and Wood theory was confirmed as a reliable basis for examining more complex surface geometries, such as turbine blades [2], and variables such as sweep.

Although these results were obtained for a circular cylinder it is useful to ask whether the approach might form a basis for predicting streamwise vorticity on turbine blade suction surfaces. These typically have a rounded leading edge and subsequently 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. It has been found that if the diameter of the suction surface osculating circle is determined at the 10% true chord location as the value of D for comparison with the Kestin and Wood theory, that theory provides a useful correlation for the spanwise wavelength of the suction surface streamwise vorticity on turbine and compressor blades.

The measurements of the spanwise wavelength of the array of vortices on turbine blade suction surfaces are compared with the predictions of Kestin and Wood in Fig. 5. Surface flow visualization photographs have been analyzed from the work of a number of published experiments on blading [6,9,10]. When examined in the same way as the surface flow visualization from the NRC turbine cascade three further results from turbine blading were accessible. Figure 5 demonstrates that these also gave reasonable agreement with the Kestin and Wood theory and experiments. Free-stream turbulence levels for the above cases were all in the range $0.2\% \leq Tu \leq 4.0\%$.

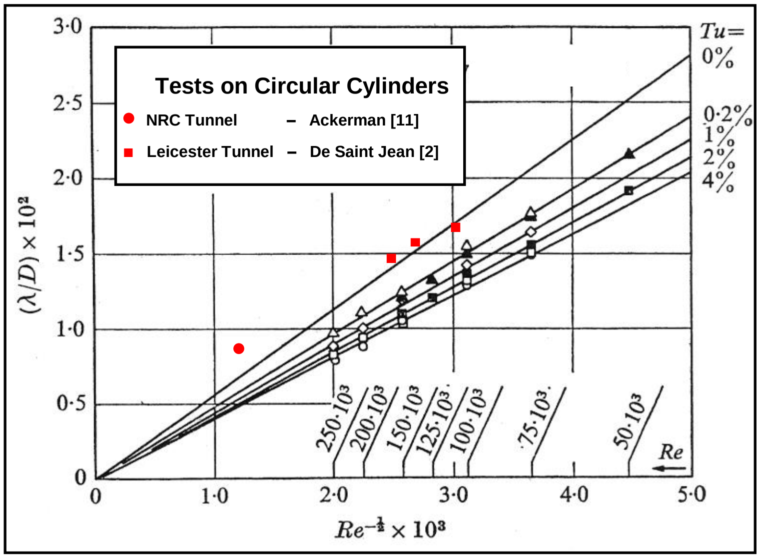

Figure 4. Measurements of Spanwise Wavelength on Circular Cylinders and Comparison with Kestin and Wood Predictions.

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 encompass this possibility. These applications often also have an appreciable degree of sweep and it is appropriate to enquire how sweep affects the instabilities. The question of sweep is addressed in Section IV.

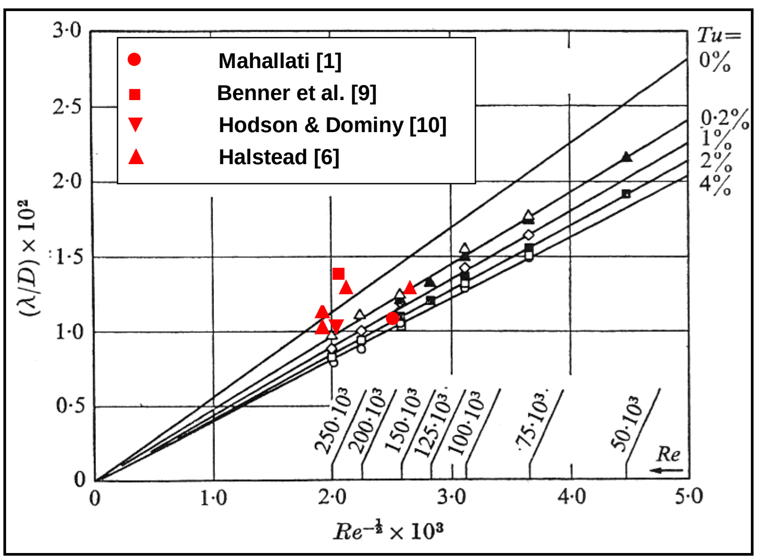

Figure 5. Measurements of Spanwise Wavelength on Blading Compared with Kestin and Wood Predictions.

IV. Sweep

The Effects of Sweep

Sweep is encountered or employed widely in the natural and physical worlds. It can be used very deliberately on the wings of high speed aircraft and on turbines and compressors. One familiar use is the alleviation of adverse effects of shock waves. In low pressure turbines the blades might be stacked in a purely radial direction but the through-flow streamlines themselves may have a strong radial component. The expansion of the working fluid dictates the required flow path area increase; this is locally presented as blade sweep. Circular cylinders are being studied to gain an understanding of sweep effects. Turbine blades inherently have a more complex geometry than cylinders but would benefit from a more complete understanding of flows about a swept cylinder. In the development of high speed wings, with high Reynolds numbers, encounters with sweep invoked its role in causing early transition from the leading edge region. In turbomachinery, the Reynolds numbers tend to be lower and the situation is less obvious. Until further clarification is achieved, it is prudent to assume that a number of modes may be competing. The effect of sweep on circular cylinders has not been fully documented and there is much work to be done experimentally and computationally before a thorough understanding may be claimed.

The results of Kestin and Wood are a good starting point for a discussion of these effects. Although the work is related to unswept cylinders, it also provides an excellent benchmark for sweep effects on cylinders and blades. This was confirmed by the experimental results of Fig. 4. These demonstrate that the formula of Eq. (1), for the lateral spacing of streamwise vortex pairs as a function of Reynolds number, gives a firm foundation for viewing other stability investigations.

The principal published collection of experimental results for high sweep angles is that of Poll [7] on a cylindrical model covering the range $55^o < \Lambda < 71^o$. Data in the useful range of sweep up to 50^o are virtually non-existent although the experiments of Takagi *et al.* [8] and Kohama [12] are of interest. The former gives an experimental point at 50^o sweep and the latter gives an intriguing photograph showing two stationary modes interacting. It is of interest to designers to develop an understanding of when the vigorous crossflow instability mode is expected. Liquid crystal work [13] suggests that cross-flow instability is first observed at around 40^o sweep and becomes most strongly amplified at around 57^o.

Transverse Spacing

Testing was carried out in the Leicester University wind tunnel over a range of Reynolds numbers from 132,000 to 175,000 and over the range of sweep angles from 0 to 60.1 degrees. These available Reynolds numbers were relatively low. Poll [7] had found that, at a Reynolds number below 339,000, streaks were only visible quite late on the surface. In the current observations streaks were faint but visible and consistent much further forward. It was found that, if sufficient care was taken with the surface coating and the optical techniques, streaks were visible in all cases. Figure 6 is a visualization record of both upper and lower quadrants, from the leading edge to laminar separation. It gives an idea of the streak spacings and angles and also acts as a check on the symmetry of the two surfaces. It demonstrates that the flow over the two surfaces behaves in a similar manner and is not noticeably influenced by gravitational or other effects.

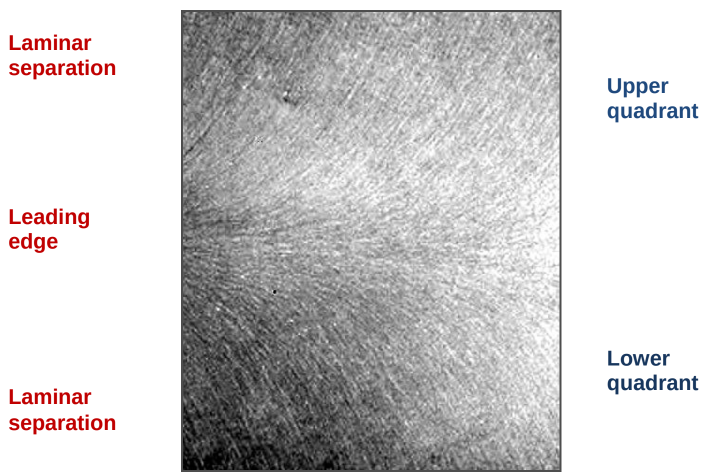

Figure 6. Variation of Streaks from Leading Edge to Laminar Separation.

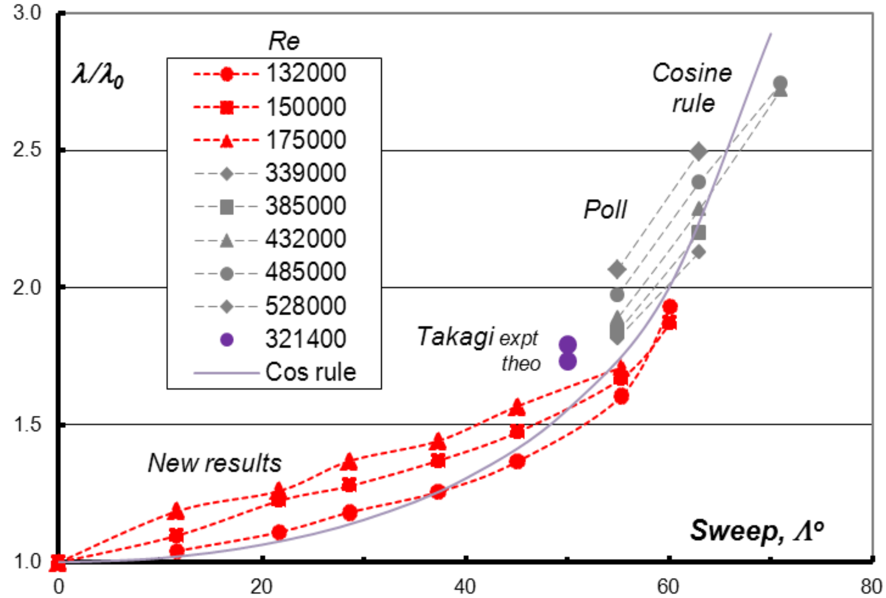

Figure 7. Lateral Spacing between Streaks Normalized by Eq. (1).

Care was taken to check that the new wind tunnel results and the results of Poll were quoted and normalized in the same way, using Eq. (1) as a reference. Kestin and Wood's theoretical result is accessible and represents very closely a regression line fit through our new experimental results for unswept cylinders. Different first order approaches to generalizing the Kestin and Wood's prediction of vortex spacing (Eq. 1) to non-zero sweep angle resulted in the same simple modification:

$$\lambda = 1.79\pi\, D / \mathrm{Re}^{0.5} \cos(\Lambda). \tag{2}$$

This is the traditional Cosine Rule used to predict sweep effects on airfoils. This approach had been found to be valid only for subcritical flows with a critical Reynolds number that decreased with increasing sweep [14]. It will be seen that $\lambda/\lambda_0 = 1/\cos\Lambda$ is a reasonable descriptor of the measurements over the sweep angle range 0^o to 60.1^o.

Equation (2) is used to plot the lateral vortex spacing, normalized by the unswept case, in Fig. 7. These results are self-consistent and also compatible with Poll's results, which were obtained at higher Reynolds numbers. The $\lambda/\lambda_0 = 1/\cos\Lambda$ theoretical curve is also plotted and demonstrates reasonable agreement with both the Poll data and the new data. At 50^o sweep the theoretical and experimental points of Takagi *et al.* [8] involved ingenious use of theory and hot wire data to discriminate between stability modes. Takagi discovered that at 50^o sweep the cross-flow mode dominated; this is the same mode identified by Poll and it is the lateral spacing from the crossflow mode that is plotted in Fig. 7. Takagi also examined the mode caused by streamline curvature from the upstream free stream. This appears to be mostly a result of the local concave streamline curvature ahead of attachment that moderates the stabilizing effect of the cylinder's convex surface. At low Reynolds Numbers Takagi found that the streamline curvature mode persisted much longer than the crossflow mode.

Takagi's results are broadly consistent with the new results and those of Poll. Full data sets were obtained at 55^o sweep, by Poll and from the current tests. These are of particular value in determining consistency; the lateral sweep spacings are plotted in the form of $100\lambda/D$ as a function of $1000/(\mathrm{Re})^{1/2}$ in Fig. 8. The present results and that of Ackerman [11], both from an unswept cylinder, are also quite well represented by a straight line. Despite the large gap in the intermediate Reynolds number range it is instructive to compare the experimental results with those from the equivalent cosine rule lines. This comparison confirms that the present results are reasonably compatible with those of Poll although the Poll results do indicate a change toward higher lateral spacings at high Reynolds numbers. This could be evidence of the conditions associated with the change in mode from the contra-rotating streamwise vorticity at zero sweep to the co-rotating vorticity usually associated with high sweep angles. The inclusion of a point from Takagi's experiment is also of interest. Although the sweep angle for the Takagi result was 50^o instead of the 55^o of the other experiments it falls on the 55^o sweep line. This therefore reinforces the observations of wider spacings encountered at high sweep. Since Takagi was able to clearly identify this point as

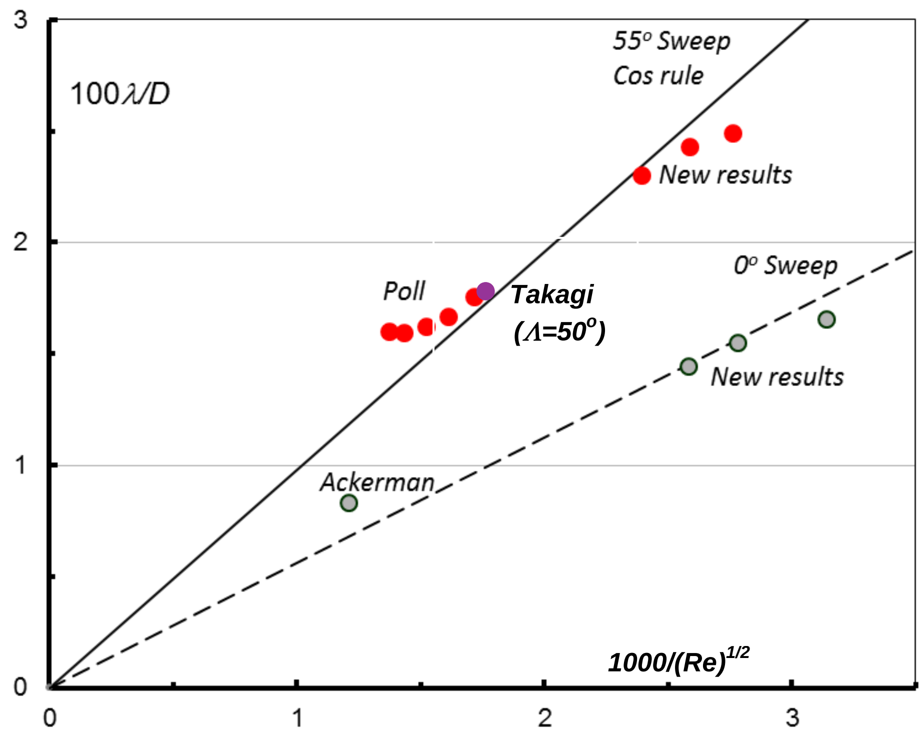

Figure 8. Reynolds Number Effects on Streak Spacing of Poll Data and Present Data.

driven by a crossflow instability the evidence supports a qualitative difference between the streamwise instability at zero sweep and low Reynolds Numbers and the crossflow instability at high sweep and high Reynolds Numbers.

The streamwise disturbance has been found to be resilient, often persisting from leading edge to trailing edge. Crossflow instability becomes more significant as sweep is increased. It grows aggressively and rapidly. It appears to be predominantly of a traveling nature, and has a major role to play in the transition process. A good summary of the difference between the two modes is given by Tokugawa *et al.*[15]:- *"Detailed observations, however, show that the crossflow mode decays with the distance from the source much faster than the streamline-curvature mode and allows the latter to be dominant in a region further downstream."*

Although most of the available information on fine structures comes from surface flow visualization, work is now progressing on hot wire measurements away from the surface. The aim is to demonstrate the relationship between the structures and the surface traces. Analysis of the data is complemented by ongoing theoretical work. It is also hoped to provide more information on the changing behavior of the vorticity as the sweep angle is increased.

Turbine blades may exhibit extremes of surface curvature, both convex and concave, pressure gradient, both favorable and adverse, leading edge bluntness, temperature, Reynolds Number and Mach Number. As a consequence turbine blades are susceptible to the different modes and it should not have come as such a surprise that these instability modes exist. Given their potential role in boundary layer transition and its modeling, in heat transfer and in blade sweep it seems important to be fully aware of the modes and their incorporation into the blade design process. The observed streaks, both stationary and traveling and of the various modes, could be of particular relevance for the thermal design of turbine blades. It is hoped to give designers confidence about the flow regimes they might anticipate for a given sweep angle and particularly of when and how the vigorous crossflow instability mode is likely to be encountered.

V. Conclusions

Experimental work has confirmed the suitability of the zero-sweep Kestin and Wood theory [4] as a basis for predicting streamwise streaks and vortical structures on unswept cylinders. High speed testing was undertaken on a

38 mm diameter cylinder and low-speed testing on a 152 mm diameter cylinder. Although the Kestin and Wood work is related to unswept circular cylinders, it also provides an excellent benchmark for sweep effects.

This work has shown that organized and systemic fine-scale streamwise vorticity may occur more frequently on convex surfaces than hitherto appreciated. Both experiments and numerical predictions should be extended to encompass that possibility. The conventional view of purely two-dimensional laminar boundary layers following blunt leading edges is not realistic. Such boundary layers need to be treated three-dimensionally, particularly when sweep is present. This requires a sufficiently fine spanwise spacing for the streamwise structures to be resolved. Application of computational methods to these problems is likely to be expensive. A combined approach of analysis, computation and experiment is indicated. Streaks observed by surface flow visualization do have significance; they are not mere artefacts of the visualization medium.

Experimental work, confirming the zero-sweep results, gave a reference for subsequent work over a wide range of sweep angles. No data had been published on streamwise and crossflow vortices in the useful sweep range of up to 50^o. Testing has been undertaken over a range of sweep angles from zero to 61^o giving results for the lateral spacing and angular orientation of the streaks. At high-sweep angles, the results are consistent with those of Poll [7]. At low Reynolds numbers first order-theories for circular cylinders predict the effects of sweep quite well. The approach of Takagi *et al.* [8] using hot wire techniques, offers an opportunity to identify both stationary and traveling instability modes.

Acknowledgments

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