15th International Symposium on Transport Phenomena and Dynamics of Rotating Machinery, ISROMAC-15
February 24 - 28, 2014, Honolulu, HI, USA

STABILITY MODES IN VORTEX STRUCTURE FORMATION: CANONICAL EXAMPLES FOR ROTATING COMPONENTS

J. P. Gostelow*, S. J. Garrett, A. Rona and D. S. Adebayo
University of Leicester, University Road, Leicester, LE1 7RH, U.K.

Abstract

Three rather different physical cases have been studied. All represent very practical geometries for which the modal behavior of vortex structures is not completely understood. The work on these problems is ongoing with the objective of obtaining physical confirmation, enhanced understanding and predictive capability for the vortex structures encountered in rotating machines.

1. Surface Flows over Rotating Cones.

Experimental studies have shown that the boundary-layer flow over a rotating cone is susceptible to cross-flow and centrifugal instability modes of a spiral nature, depending on the cone sharpness. For apex half-angles (ψ) ranging from propeller nose cones to rotating disks ($\psi \geq 40^{\circ}$), the instability triggers co-rotating vortices, whereas for sharp spinning missiles ($\psi < 40^{\circ}$), counter-rotating vortices are observed. A mathematical description is provided of the onset of co-rotating vortices for a family of cones rotating in quiescent fluid, with a view towards explaining the effect of ψ on the underlying transition of dominant instability using numerical and asymptotic methods. The stability of inviscid cross-flow modes (type I) is investigated, as well as modes arising from a viscous–Coriolis force balance (type II). The influence of ψ on the number and orientation of the spiral vortices is examined, with comparisons drawn between the two distinct methods as well as with previous experimental studies. The results indicate that increasing ψ has a stabilizing effect on both the type I and type II modes. Favorable agreement is obtained between the numerical and asymptotic methods presented here and existing experimental results for $\psi > 40^{\circ}$. Below this half-angle it appears that an alternative instability mechanism is at work, which is not amenable to investigation using the broad-cone formulation. An alternative formulation has been developed and properties of the counter-rotating vortices successfully predicted.

2. Turbine Blades and Swept Cylinders.

Suction surface flow visualization on turbine blades at subsonic and transonic speeds showed robust streamwise streaks on a lengthy time-average basis [1] (Fig. 1). The flow on the suction surface, under the influence of a strong favorable pressure gradient, was initially laminar. Further downstream laminar separation and transition to turbulence were encountered. The turbulent boundary layer region then persisted to the trailing edge. The streamwise streaks were unaffected throughout the whole surface regardless of the boundary layer state. Similar behavior was observed by Halstead [2], who had surface film confirmation of the boundary layer state throughout. The streamwise vortex structures, whilst not particularly strong, are persistent and would seem to exert a stabilizing influence on the flow. The lateral spacing between streaks on convex surfaces had been predicted by Kestin and Wood [3].

Observations of streaks on turbine blades and unswept cylinders were to provide a firm basis for referencing the influence of sweep. High speed testing was undertaken on a 38 mm diameter cylinder and low-speed testing on an unswept 152 mm diameter cylinder. The results are in excellent agreement with the Kestin and Wood theory, providing confirmation of the theory for circular cylinders. Although the Kestin and Wood work is related to unswept circular cylinders it also provides an excellent benchmark for sweep effects on turbomachinery blading. The introduction of sweep brings consideration of a wide range of instabilities. Crossflow instability results from the inflectional behavior of a three-dimensional boundary layer and is thought to be prominent and aggressive. Experimental work on a circular cylinder has been undertaken by the authors over a range of sweep angles from zero to 61°, giving results for lateral spacing and angular orientation of the vortical streaks. Figure 2 demonstrates that at high-sweep angles the results are consistent with those of Poll [4] and of Takagi *et al.* [5]. It is shown that

* Corresponding author. Email: jpg7@le.ac.uk, tel: +44(0)116 252 2570

streamwise and crossflow structures are present on the suction surface of swept and unswept turbine blades. 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. It is also hoped to provide information on the changing behavior of the spanwise velocity field as the sweep angle is increased. The streamline curvature disturbance has been found to be stationary in nature and to be resilient. The 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.

3. Taylor Vortices between Rotating Cylinders with Wide Gap.

Taylor vortices develop in the gap between concentric rotating cylinders when the Taylor number exceeds the first critical value. Concentric rotating cylinders with radius ratio $\eta = 0.53$, aspect ratio $\Gamma = 11.36$ and $\mu = 0$ have been investigated by Particle Image Velocimetry. The test case is characterized by a larger annular gap width d than classical journal bearing test cases and by a Taylor number range $2.36 \times 10^6 \leq Ta \leq 6.37 \times 10^6$, that is beyond the first critical Taylor number at which Taylor vortices develop. Some interesting flow features are observed in this region of flow parameters. Analytical results at the azimuthal wave-number $m = 3$ show a pattern that deviates from the linear trend reported in previous literature as the radius ratio $\eta \leq 0.6$. This amounts to the onset of a new behavior at this radius ratio, as further indicated by a step change in the gradient of the predicted variation of the axial wave-number and of the azimuthal wave velocity at a radius ratio of $\eta = 0.65$.

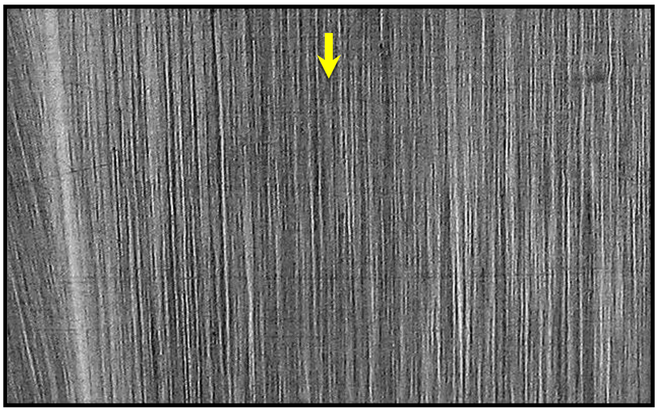

Fig. 1. Suction Surface Flow Visualization between 80% and 95% Axial Chord of NRC Turbine Blade at a Discharge Mach Number of 1.16.

The flow pattern and variables from Particle Image Velocimetry at $\eta = 0.53$ show wavy vortical structure in the flow between the concentric cylinders with low aspect ratio $\Gamma < 25$ and at a high Taylor number, well beyond the published values for transition to turbulent flow. This regime is characterized by enhanced waviness near the end-walls as compared with the wavy flow in the central region. The flow does not break up to a turbulent state for this test case. At the tested Taylor number, the experimental result suggests that an odd azimuthal wave-number persists in this range of the flow parameters.

References

[1] Gostelow, J. P., Mahallati, A., Carscallen, W. E. and Rona, A., 2010, "Organized Streamwise Vorticity on Convex Surfaces with Particular Reference to Turbine Blades," *48th AIAA Aerospace Sciences Meeting, Orlando*, AIAA 2010-904.

[2] Halstead, D. E., 1989, "The Use of Surface-Mounted Hot-Film Sensors to Detect Turbine-Blade Boundary-Layer Transition and Separation", *Master of Science Thesis, Iowa State University*.

[3] Kestin, J., and Wood, R. T., 1970, "On the Stability of Two-Dimensional Stagnation Flow," *Journal of Fluid Mechanics*, 44:461-479.

[4] Poll, D. I. A., 1985, "Some Observations of the Transition Process on the Windward Face of a Long Yawed Cylinder," *Journal of Fluid Mechanics*, 150:329-356.

[5] Takagi, S., Tokugawa, N. and Itoh, N., "Characteristics of Unsteady Disturbances due to Streamline Curvature Instability in a Three-Dimensional Boundary Layer," 2006, *Proc. 6th IUTAM Symposium. on Laminar-Turbulent Transition*, R. Govindarajam, ed. Springer, pp. 369-374.

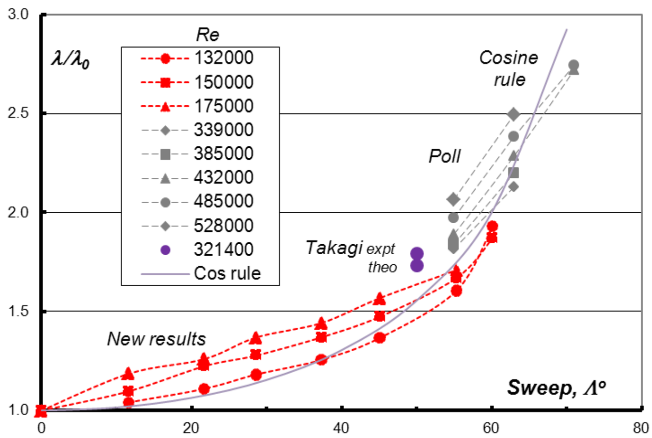

Fig. 2. Normalized Lateral Spacing between Surface Flow Visualization Streaks on a Swept Cylinder.