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"AERODYNAMICS OF VORTEX GENERATORS"*

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Abstract

An experimental and theoretical study was undertaken of the separation delay and dramatic boundary-layer thinning that can occur in vortex-generator installations. Wind tunnel measurements of the dynamic-pressure profile downstream of a vortex generator were found to compare under certain conditions with that downstream of a suction slit, while water-tunnel visualization studies of vortex-generator height and geometry suggested optimum configurations, and only a minor effect of base porosity. A series of progressively more complex inviscid flow models was developed to be applied to a 3-D integral boundary-layer code. This code predicted layer thinning downstream of the suction site of the vortex models, and other observed features. Thin-layer Navier Stokes equations are now being used with the ultimate goal of clarifying the physical processes involved in vortex generator performance and developing calculational procedures capable of predicting it.

Introduction

Vortex generators are used on the wings of commercial transports, on wind turbine blades, on internal diffusing flows, and on any situation where control of boundary-layer separation and reattachment is desired. Extremely simple in concept, they usually consist of tiny plates attached to the surface and protruding normal to it. They are set at an angle to the free stream and thus act as small lifting surfaces with each producing a strong axial vortex that trails downstream. This vortex interacts with the rest of the wall layer, and mixes external fluid into it to energize the layer and modify its behavior.

Vortex generators were apparently first used by H.D. Taylor at United Aircraft(1). A systematic experimental study of their performance was subsequently made by Shubauer and Spangenberg at the National Bureau of Standards(2). The work of Pearcey(3) sets a solid foundation by cataloging types of generators, dynamic features of the vortices produced, and overall effectiveness under certain conditions. However, no models have yet been introduced to predict the separation delay and dramatic boundary-layer thinning that can occur. Because of this lack of fundamental knowledge, engineers are restricted to using rules-of-thumb combined with extensive testing. A better understanding could lead to higher wing performance in cruise and maneuver, simpler landing configurations, more efficient rotors, turbine blades and diffusers, and better control of base drag.

An experimental and theoretical study of vortex generator aerodynamics has been carried out at the University of Washington under NASA sponsorship. The results are summarized in the next two sections and the associated references. The work is continuing, and the third section describes more recent results.

Experimentation

After early hot-wire measurements, the laboratory experiments focussed on two topics[4]. The first concerned the hypothesis that the effectiveness of vortices for boundary-layer thinning was due to a spanwise stretching caused by turbulent entrainment, and thus similar to that expected from a line sink along the wall. The second topic was a study of vortex generator design for creating a strong vortex at optimum height with least parasitic drag. Induced drag is inevitable as energy is invested in the shed vortex, however the parasite drag associated with flow separation around the vane element reduces the lift and hence the tip vortex strength.

Wind tunnel experiments: The boundary-layer thinning experiments were carried out in a 0.3 x 2.4m cross-section open-circuit wind tunnel. A 0.6 cm-wide slot, 0.3 m-long in the flow direction, was located in the middle of a 2.4m wall and connected to a plenum and a 0.24 kgm/sec suction pump. The tunnel speed was then set to give ratios of slot suction velocity to speed of 2.4-4.8, and profiles of the boundary layer edge taken at a station just downstream of the slot. The profiles were also measured 0.6m downstream of a 2.8 x 11.2 cm long flat-plate vortex generator set at various angles of attack in a separate set of experiments.

The results were compared with simple models for a distributed line sink and a self-similar turbulent vortex. It was found that the width of the region of boundary-layer thinning, defined as where the dynamic pressure had dropped to 80% of the free stream value, increased with the suction velocity ratio in a linear fashion as predicted. The thinning half-width profile on the low-pressure side of the vortex generator at angle of attack of 6° was found to be close to that of the slit for velocity ratio 2.4. However these experiments showed considerable scatter, presumably due to the high turbulence levels close to the wall.

Flow visualization experiments: these were conducted in a free-surface water tunnel facility with a 7.3m test section of width 31 cm and depth 52 cm. An 84 cm long flapped lucite plate with an elliptical leading edge spanned the test section and was suspended off the bottom. Vortex generators at an angle-of-attack of 15° were taped to the plate at 20 and 22 cm from the leading edge, and dye was injected by gravity through a slot located at 15 cm. These experiments were at low Reynolds number, thus the flow was laminar and the streaming motion of the dye made the streamlines clear. The first set of generators were rectangular with a height-to-length ratio of $^1/_4$; it was found that the one with a 6.4 mm height, about twice the depth of the dyed layer, was observed to produce the most noticeable results. The second set include square, delta, triangular, and truncated rectangular plan forms, all with a height of 6.4 mm. Although the effects were in some cases significantly different, none were very unusual(4). The final set were truncated rectangles with holes drilled through at the root. The concept here was to inject high energy flow from the pressure side of the vane into anemic regions on the suction side in order to minimize the separation and thereby increase the vortex strength. Although increased porosity did displace the flow pattern of the dye, there was no evidence that it modified the character of the flow.

Calculation/Modelling

The hot-wire experiments and preceding studies(3) have shown a dramatic thinning of the boundary-layer between counter-rotating vortex generators, with the reduced thickness nearly constant over most of 10-30 undisturbed layer-thickness distance between them. A major objective of the modelling has been to predict this effect, which must be due to the importance of vortex-induced crossflow and the associated turbulent entrainment. The initial procedure has been to model the incompressible inviscid flow from the generators in a uniform free stream, and then apply this as the flow driving a 3-D incompressible boundary-layer development. As summarized in reference 5, the study was thus divided into both inviscid and viscous modelling and calculation.

Inviscid modelling: Four different basic potential flows were used, all ultimately applied to a flat plate at zero angle of attack. The first was simply a crossflow velocity increasing linearly from zero in the spanwise direction and added to a uniform free stream. Because of a concern that the inviscid flow satisfy continuity, the second flow was that from a 3-D source placed upstream in the plane of the wing. Next a uniform line sink across the wing chord was superimposed on a uniform approach stream, and the results applied for cases with the line sink at the wing tip and also moved off in order to avoid singularities. Finally, real vortices were modelled and used.

Studies have clearly shown that the vortex from the tip of a lifting wing rolls up and is well-formed within a few chord-lengths downstream. Further, subsequent viscous modification takes a long time or length scale, even for turbulent flows. Thus the vortex generators can be treated as half-span lifting wings with ideal inviscid vortices initially shed from their tips. A simple program was set up to calculate the velocity field from a single vortex and its image across the wing plane, for an arbitrary number of initially equally-spaced co-rotating vortices with their images, for a cell consisting of two counter-rotating vortices and their images, and for a general array of the latter. The vortices will move with respect to each other and the plane of symmetry as one progresses downstream. While a small effect for the present study, that has been calculated and checked. Finally a program has been setup to calculate the streamlines on the plane of symmetry, this being a logical input for the boundary layer program. For the basic counter rotating cell in a uniform approach stream this shows that streamlines from the leading edge on the low pressure side can cross over and intercept those from the high pressure side leading edge, leading to a phenomena corresponding to separation.

Viscous calculation: A 3-D boundary-layer integral method based on the work of P.D. Smith [(6)] was chosen for reasons of speed and economy. This uses momentum and moment-of-momentum equations in both the streamwise and cross flow direction, uses a Stewartson compressibility transformation, and assumes a power-law streamwise velocity profile and a Mager cross flow profile. The system of equations ultimately reduces to three which are numerically solved for the streamwise momentum thickness, shape factor, and wall shear. The system of equations is hyperbolic in nature, exhibiting zones of dependence; it relies on empiricism when dealing with turbulent flow.

A built in test case for a transonic air foil was run successfully, as was a Blasius boundary layer. Runs were then made using each of the inviscid models for the external flow just discussed, applied to a flat plate wing of chord 3m at zero angle-of-attack with a 100 m/sec approach velocity. A square plan form generator of dimension equal to the turbulent layer thickness at 0.5m and at 15° angle of attack was calculated to produce a circulation of 0.75 m^2/sec.

Calculations with the linearly increasing cross flow gave encouraging spanwise variations of displacement and momentum thickness, but showed implausible results at the tip and root planes, including violations of symmetry. The source flow was expected to show a thinning due to the cross flow component, competing with a thickening near the tip due to increased distance from the source. The calculations did show the expected thinning at the root, but with a rapid increase in thickness near the tip. Root plane assymetry was no longer a problem, however moving the source closer to the leading edge led to large regions of separation due to the adverse pressure gradient. The displacement thickness was found to decrease in both the spanwise and free-stream directions for the distributed line source case, however the results were clouded by large excursions near the tip. It was hoped to alleviate singularity problems in the actual vortex flows by avoiding stations near the cores, or by inputting the velocity field at the wing plane of symmetry. Very clear results were obtained for the momentum thickness variation with span, showing a thinning that depended approximately linearly on the strength of the circulation, and a pile up or thickening on the high pressure side. Problems with separation and the resulting propagation of an increasingly large region of indeterminant solution could be relieved by adding a mild acceleration to the free stream flow. Effects of the applied velocity normal to the wing plane were generally small, as expected.

Current Research

Studies of vortex generator aerodynamics have continued with student support from the university, computer codes and run time from industry , and some supercomputer time from the National Science Foundation. The current emphasis is on numerical prediction, and integral methods have been put aside in favor of full finite-difference techniques. While experience has been gained with application of a 3-D finite-difference boundary-layer code, complete equations are now in use which allow for pressure gradients in the cross-flow plane, as well as calculation through somewhat better handling of separated regions. The full Navier-Stokes equations are still too complex and require extensive computer time and storage, and the best compromise appears to be the parabolized or thin-layer Navier Stokes equations. While producing very good results in supersonic flows, this system requires further modification to account for the upstream influence in the case of subsonic flow. Here a global iterative procedure for the pressure field is used, resulting in a "partially-parabolized" system.

A proven parabolized code has been acquired from a local firm, and is now modified for subsonic use. Successful runs have been made with systems of strong vortices initiated over the leading edge of a flat plate, applying the zero-slip condition at the plate plane of symmetry. While the mesh is still too coarse to see boundary-layer details, vector plots of the velocity and vorticity fields show many plausible features as the flow proceeds downstream, including expected movement and shape change of the core region and initiation of secondary vortices at the wall. The 2-D turbulent flat plate boundary-layer case has now been run, and mesh refinement is being carried out in order to explore boundary-layer behavior in the presence of streaming vorticity. This will require assumption of a small initial viscous core in the vortices, in addition to an initial boundary-layer profile.

Once proven out, the code will be applied to investigate the effects of wing angle of attack, and airfoil, as well as relative vortex strength, location and spacing on wing aerodynamics. The numerical runs will include cross-flow-plane dynamic-pressure profiles over extreme conditions, and will explore the effects of this cross-flow in a search for insight into simple performance models. The applicability of the boundary-layer equations will then be revisited, and small perturbation models sought. Ultimately the study may again include experimentation, and may extend to transverse jets, compressibility, and flow features of importance to high speed mixing.

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