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"Investigation of the relationship of vortex-generated sound and airframe noise"

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Abstract

Airframe noise contributes the most to the environmental contamination from airports during take-off and landing. Two sources of noise are from the vortex-system associated with the slat and flap of multi-element wing designs. The flap-side edge vortex experiences bursting, known as vortex breakdown, at a critical deflection angle and experimental results show that this event may be one source of increased noise levels. Understanding of the edge roll-up phenomenon has increased but further focused studies on the role of the growth and bursting of the vortex structure are needed[1]. The goal of the research is to plan a research program that will contribute to the understanding of the fluid physics of vortex breakdown and its relationship to noise production. The success of this program will lead to *a priori* predictions of when vortex breakdown will occur on the flap side-edge and accurate calculations of its effect on the noise level experienced by an observer near the aircraft during take-off and landing.

1. Introduction

Airframe noise contributes the most to the environmental contamination from airports during take-off and landing. Two sources of noise are from the vortex-system associated with the slat and flap of multi-element wing designs. The flap-side edge vortex experiences bursting, known as vortex breakdown, at a critical deflection angle and experimental results show that this event may be a source of increased noise levels. Understanding of the edge roll-up phenomenon has increased but further studies on the specific role of the growth and bursting of the vortex structure in aerodynamic noise production are needed[1].

Vortex breakdown refers to the sudden appearance of a stagnation point on the vortex axis followed by finite region of reversed flow. Two types of breakdown have been identified: the axisymmetric or bubble type and the asymmetric or spiral type. Both types exhibit a sudden expansion of the vortex core although the magnitude of the core expansion, as measured by the core expansion ratio (wake vortex core / approach vortex core), for the bubble-type breakdown is much larger than that for the spiral breakdown. It is the spiral vortex breakdown that occurs in towing tank experiments with delta wings[2].

The exact causes of vortex breakdown are unknown and remain a controversial aspect of vortex dynamics. The initial approach was that vortex breakdown was the result of hydrodynamic instabilities in the mean flow in which the vortex flow was a stable secondary flow. Models of this type were built on the small-disturbance theory that was also used in the early transition research. The theoretical work by Benjamin [4] refuted these theories and showed that the phenomenon was actually a transition between two dynamically conjugate flow states, analogous to the hydraulic jump in open channel flows. This result was bolstered by the experiments of Harvey [5] in which a cylindrical vortex in a tube was used to study the vortex breakdown of the type that occurs over slender delta wings. He too found that the breakdown of the vortex was the intermediate stage of two types of rotating flows - those that do and those that do not exhibit axial flow reversal.

Benjamin [4] and Harvey's [5] results were later refuted by Bossel [6]. Upon solving a linearized version of the axisymmetric equations using a series solution, he concluded that vortex breakdown is neither due to hydrodynamic stability nor analogous to the hydraulic jump. The phenomenon was shown to be a regular solution of the equations of motion when retardation of the axial velocity at high swirl is introduced. His results also showed that the breakdown is primarily an inviscid phenomenon in which the value of the swirl parameter is the determining factor of whether or not a breakdown will occur. This approach is still adopted and has been related to the general problem of existence and uniqueness of solutions of the steady, incompressible Euler equations [7].

Sarpkaya [8] focused on the type of breakdowns that can occur for given flow conditions. In his experimental investigation of vortex breakdown three types were observed: mild breakdown (double helix), spiral breakdown, and axisymmetric breakdown. Mager [9] found that the spiral breakdown is the trigger for the formation upstream of the axisymmetric (bubble) type breakdown and the asymmetric departure of the flow from its quasi-cylindrical form. He also demonstrated that the effect of an adverse pressure gradient is to shift the position of the breakdown location farther upstream. This was demonstrated in another experiment by Sarpkaya [8] who further noted that this result also occurs with an increase in circulation or mean flow rate.

Kopecky and Torrence [10] investigated the vortex breakdown phenomenon using numerical techniques. In particular they studied the vortex formation and breakdown of axisymmetric, swirling flow of an incompressible fluid through a cylindrical streamtube. Their results qualitatively agreed with those of Sarpkaya [8].

Grabowski and Berger [11] solved the full Navier-Stokes equations for the breakdown of an unconfined viscous vortex for core Reynolds numbers up to 200 using a two parameter family of assumed upstream velocity distributions. Their results show that the conclusions of previous authors that vortex-breakdown is a finite reversible transition between two states is inconsistent. Further numerical results of Salas and Kuruvila [13] for the axisymmetric case showed that the dominant parameter was the swirl, agreeing with the theoretical results of Bossel [6]

One goal of the proposed research was to contribute to the understanding of the physics of vortex breakdown enough to predict when it will occur and to determine *a priori* its effect on the noise level experienced by an observer near the aircraft during take-off and landing. Specifically, the results of the research program should demonstrate the importance of vortex-generated sound on the overall noise level generated by the airframe.

2. Problem Statement and Approach

The results in the literature cited above suggest that the axisymmetric (bubble) vortex breakdown is limited to internal flows (e.g. flows in tubes) and the asymmetric (spiral) vortex breakdown is more characteristic of external flows such as those over aircraft wings. Since the spiral type of breakdown is more characteristic of the flows over single-element wings, one would expect by extension that this too would be the case for the flap side-edge of a multi-element airfoil. However initial experimental results from NASA Langley Research Center (NASA LaRC) Airframe Noise Reduction Program show that the flap side-edge vortex breakdown has the character of the axisymmetric bubble. One of the tasks in this work will be to provide a physical explanation for this phenomena.

One clue lies in the work of Mager mentioned in Section 1. Recall that he showed that the asymmetric (spiral) breakdown can act as a trigger for the formation of the axisymmetric (bubble) vortex breakdown. The principal investigator (PI) investigated the use of some of the methods from nonlinear hydrodynamic stability and transition as in Smith[17] and Smith and Haj-Hariri[18] to show that the mean flow around the flap is able to sustain the spiral as a stable secondary flow long enough for it to transition into the next state which would be the bubble. The formation and transition from one vortex-dominated flow to another is expected to be governed by the relationship of the critical deflection angle to the circulation and the instability of vorticity around the flap side-edge. Experimental results from NASA LaRC report a bubble type of breakdown over the flap side edge at a critical deformation angle of 39°[19]. The scientific questions to be answered are then: What characteristics are required of the mean flow to support the transition from spiral to bubble and why are they not present on single-element delta wings? It is expected that answers will be attributable to the continual feed of vorticity reported by Streett[20].

Mager also reported that the effect of an adverse pressure gradient on vortex breakdown was to move the breakdown location farther upstream. The adverse pressure gradient for the flap becomes more severe with increasing flap deflection angle. When the vortex breakdown occurs it appears to move forward and lock at a location above the flap where it interacts with the surface. This interaction is a potential source of the noise. Understanding the physical mechanisms that produce vortex breakdown is essential to to reducing noise from this source.

The experimental results from NASA LaRC with respect to the issues of the unexpected occurrence of the axisymmetric vortex-breakdown and the vortex behavior resulting from the adverse pressure gradient, suggest that the flap side-edge vortex dynamics are very similar to those reported in the results from the early vortex-breakdown experiments in tubes. Some of the early theoretical work, especially the instability theories, gave results that were qualitatively in agreement with some of the these experiments. The PI reconsidered some of the previously dismissed theoretical work to investigate its applicability to this *particular* flow field.

3. Results

All of the funds were used for the PI to spend 1.5 months during the summer (5/18/98-6/30/98) at NASA Langley Research Center (LaRC). The purpose of the visit was to permit the PI to become familiar with the experimental work being conducted by Boeing and NASA LaRC in the airframe noise program in general but specifically those results concerning vortex-breakdown. Experimental results from the NASA-Langley Quiet Flow Facility indicated that bursting of the flap-side edge vortex occurred for critical deflection angle of 39° [21]. The rpimary result of the summer research was that the initialstability approach was insufficient to resolve the disparate scales involved in the bursting. Also, the stability analysis approach would not provide any information of the necessary turbulence required for the acoustical analysis. It was decided that to find that best approach a two-fold investigation would take place. The investigation of the use of a so-called unsteady Reynolds Averaged Navier-Stokes (RANS) calculation would be and a Large Eddy Simulation (LES) calculation to resolve the turbulence and the scales of the vortex-bursting. This study will be proposed for the new Airframe Systems Base Research and Technology Program.

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September 20, 1999

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To whom it may concern,

Please find enclosed a copy of the final report for grant NAG-1-2015. I would greatly appreciate your confirming receipt of this document. I can be reached by telephone at (202) 806-4837 or by Email at the address sts6f@vortex.eng.howard.edu.

Sincerely,

**Sonya T. Smith, Ph.D.
Principal Investigator**