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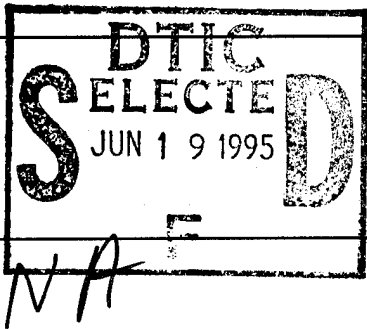
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**FINAL TECHNICAL REPORT FOR AFOSR GRANT F49620-94-1-0038**

**STRUCTURE AND CONTROL OF THREE-DIMENSIONAL UNSTEADY FLOW  
IN DELTA WINGS AT HIGH ANGLE-OF-ATTACK**

**Program Monitor:** Dr. Len Sakell

**Principal Investigator:** Professor Donald Rockwell, Department of Mechanical  
Engineering and Mechanics, Lehigh University, Bethlehem, Pennsylvania

**Duration of Grant:** 15 November 1993 to 14 November 1994

**ABSTRACT**

This program has focused on the instantaneous flow structure generated by controlled motion of wings in the pitching and rolling modes, as well as application of local control techniques for modifying the flow structure.

The instantaneous flow structure is characterized using high-image-density particle image velocimetry, in conjunction with new types of two- and three-dimensional imaging techniques. This approach provides instantaneous velocity fields, streamline patterns and vorticity distributions at crucial locations in the flow field and allows a proper basis for eventual control of the flow structure.

Characterization of the flow structure in the rolling mode of wing motion has involved definition of the critical states of the flow, based on the static locations of onset of vortex breakdown. The instantaneous crossflow and streamwise topology has been defined as a function of row angle. For pitching motion of the wing, simultaneous maneuver of the wing and application of control in the form of deflection of a leading-edge flap and blowing from the trailing-edge provide an effective, interactive means of altering the onset of vortex breakdown, thereby enhancing the effectiveness of maneuvers at high angle of attack.

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## **1. EXPERIMENTAL TECHNIQUES AND FACILITIES**

Techniques of high-image-density particle image velocimetry have focused on use of a scanning laser sheet to generate pulsed illumination, which provides well-defined images of micron-sized particles that seed the water flow. The advantage of this approach is that it provides a high repetition rate, allowing use of cinematography, and thereby images that are highly resolved in both space and time. Successful implementation of the high-image-density PIV approach has required new software developments for constructing two- and three-dimensional images of the flow, based on patterns of velocity, streamlines and vorticity. By using superposition techniques, it is possible to unambiguously identify crucial events, such as the onset of vortex breakdown. This approach involves overlay of patterns of instantaneous streamlines and contours of constant vorticity. Using these techniques, it has been possible to identify new mechanisms of vortex breakdown occurring at high angle of attack.

New types of local control techniques have been developed in conjunction with the foregoing PIV approach. Using high resolution, computer-controlled stepping motors, it is possible to simultaneously control the roll angle or angle-of-attack of the delta wing, the deflection of a leading-edge flap, and the onset and duration of blowing from the trailing-edge. These systems are controlled by a central microcomputer in the laboratory, which allows arbitrary variation of the maneuver schedule, as well as the triggering and persistence of the control events. This approach has allowed new insight into the concept of simultaneous, interactive (open-loop) control.

## **2. FLOW STRUCTURE ON A ROLLING DELTA WING**

A delta wing having a sweep angle of  $65^\circ$ , modeled on the wing employed in the series of experiments performed in the SARL facility at Wright Patterson Air Force Base, has been deployed in a large-scale water channel facility. Use of dye injection has led to definition of the location of onset of vortex breakdown as a function of static roll angle. The occurrence of abrupt changes in the location of breakdown onset, which allows definition of critical states of the flow structure, is in good agreement with the experiments performed at SARL. In addition, interactions with the Computational Fluid Dynamics Group at Wright Patterson Air Force Base has allowed direct comparison between the water channel experiments and numerical simulations.

Using the static characteristics of the location of onset of vortex breakdown as a guide, recent efforts have focused on determining the instantaneous patterns of vorticity and streamlines in both the crossflow planes and planes cutting along the axis of the leading-edge vortices. Of particular interest is the potential cross-communication between the leading-edge vortices on either side of the delta wing as a function of roll angle. Moreover, it has also become evident that the onset of vortex breakdown exhibits substantial time-dependent excursions, even for the case of the stationary wing. The possibility that such unsteady excursions could lead to triggering of a self-excited rolling

mechanism are presently under consideration. It is planned to continue these experiments, with the goal of providing new insight into the instantaneous topological features. Using critical point theory, the instantaneous velocity fields and streamline patterns will be constructed in order to determine the principal mechanisms that give rise to the asymmetry of the loading as a function of static and dynamic roll angle. In doing so, it is planned to use new types of image construction techniques in two- and three-dimensional space.

### **3. FLOW STRUCTURE AND ITS CONTROL ON A PITCHING DELTA WING**

A unique, half-delta wing subjected simultaneously to pitching motion and to local control techniques has been designed, manufactured and implemented in the large-scale water channel facility. Use of the half delta wing allows application of multiple control techniques, while the wing is undergoing controlled pitching motion. The central laboratory computer allows arbitrary variation of the sinusoidal or ramp-type pitching motion, flap deflection, and trailing-edge blowing. Particularly crucial is the proper selection of the initial and final angle of attack. The major features of dynamic hysteresis of the onset of vortex breakdown have been identified as a function of pitch rate, thereby providing a basis for application of local control techniques.

Local control in the form of stationary and unsteady flap deflection, as well as steady and time-dependent blowing from the trailing-edge of the wing have been assessed. Detailed dye injection has allowed definition of the most effective combination of control parameters. Most recently, application of the high-image-density PIV technique allows determination of the instantaneous streamline patterns and vorticity distributions in the cross-flow plane and in a plane aligned with the axis of the leading-edge vortex. By employing an appropriate combination of flap deployment and trailing-edge blowing, very substantial alterations of the onset of vortex breakdown can be attained during a maneuver. The detailed structure of the vortex breakdown region has been pursued by examination of velocity fields in a reference frame moving with the freestream velocity, which are superposed on the instantaneous distributions of vorticity. The velocity field exhibits a saddle point distribution. The geometrical form of this saddlepoint is a strong function of the angle of attack. Moreover, it appears that the onset of pronounced concentrations of vorticity can occur upstream of the location of vortex breakdown; the actual location of breakdown is defined in terms of a switch in the orientation of the positive and negative regions of vortex breakdown. A wavelet transform technique is currently under investigation. It will allow formulation of a pattern recognition procedure for determining the location of vortex breakdown, with the long-range intent of manipulating the occurrence of breakdown based on real-time identification of the primary topological features of the flow.

#### 4. PUBLICATIONS AND PARTICIPANTS

The primary journal (archival) publications, which either have been submitted, are in press, or are in print are summarized in the following:

##### PUBLICATIONS (SUBMITTED)

"Buffeting at the Leading-Edge of a Flat Plate due to Streamwise Vortex: Flow Structure and Surface Pressure Loading", submitted to *Journal of Fluids and Structures* (with S. Wolfe and J.-C. Lin).

"Buffeting of a Fin: Streamwise Evolution of Flow Structure", submitted to *AIAA Journal of Aircraft* (with S. Canbazoglu, J.-C. Lin, and S. Wolfe).

"Three-Dimensional Flow Structure on Delta Wings at High Angle-of-Attack: Experimental Concepts and Issues", submitted to *AIAA Journal*. (Also AIAA Paper No. 93-0550.)

##### PUBLICATIONS (IN PRESS)

"Three-Dimensional Patterns of Streamwise Vorticity in the Turbulent Near-Wake of a Cylinder", *Journal of Fluids and Structures* (in press) (with J.-C. Lin and P. Vorobieff).

"Flow Structure on a Stalled Delta Wing Subjected to Small-Amplitude Pitching Oscillations", *AIAA Journal* (in press) (with K. Cipolla).

"Instabilities of Separated/Swirling Flows and Flow-Acoustic Coupling", Chapter 14 in *Handbook of Fluids and Machinery* (ed. J. Schetz), John Wiley and Sons (New York) (in press).

"Buffeting of Fins: An Assessment of Surface Pressure Loading", Technical Note in *AIAA Journal* (in press) (with S. Wolfe, S. Canbazoglu, and J. C. Lin).

"Buffeting of Fin: Distortion of Incident Vortex", *AIAA Journal* (in press) (with S. Canbazoglu, J.-C. Lin and S. Wolfe).

##### PUBLICATIONS (IN PRINT)

"Quantitative Interpretation of Complex, Unsteady Flows via High-Image-Density Particle Image Velocimetry," SPIE International Symposium on Optics, Imaging and Instrumentation, San Diego, CA, 11-16 July, 1993, SPIE 2005 (with J.-C. Lin).

"Cinematographic System for High-Image-Density Particle Image Velocimetry", *Bulletin of the American Physical Society*, Vol. 38, No. 12, Abstract IG3, 301, 1993 (with J.-C. Lin and P. Vorobieff).

"Reply to Comments on Control of Vortices on a Delta Wing by Leading-Edge Injection", *AIAA Journal*, Vol. 32, No. 10, p. 2134, 1994.

"Transient Structure of Vortex Breakdown on a Delta Wing at High Angle-of-Attack", *AIAA Journal*, Vol. 33, No. 1, pp. 6-12, 1995 (with J.-C. Lin).

"Interaction of a Streamwise Vortex with a Thin Plate: A Source of Turbulent Buffeting", *AIAA Journal*, Vol. 32, No. 10, pp. 2022-2029, 1994 (with A. Mayori).

"Cinematographic System for High-Image-Density Particle Image Velocimetry", *Experiments in Fluids*, Vol. 17, pp. 110-118, 1994 (with J.-C. Lin).

Flow-Induced Vibrations: An Engineering Guide, (book), Balkema Press, Rotterdam, April, 1994 (with E. Naudascher).

"Laser-Scanning Particle Image Velocimetry Applied to a Delta Wing in Transient Maneuver", *Experiments in Fluids*, Vol. 15, No. 3, pp. 159-167, 1993 (with C. Magness and O. Robinson).

"Construction of Three-Dimensional Images of Flow Structure Via Particle Tracking Techniques", *Experiments in Fluids*, Vol. 14, pp. 257-270, 1993 (with O. Robinson).

"Instantaneous Topology of the Unsteady Leading-Edge Vortex at High Angle of Attack", *AIAA Journal*, Vol. 31, No. 8, pp. 1384-1391, 1993 (with C. Magness and O. Robinson).

"Control of Vortices on a Delta Wing by Leading-Edge Injection", *AIAA Journal*, Vol. 32, No. 7, pp. 1177-1186, 1993 (with W. Gu and O. Robinson).

"High-Image-Density Particle Image Velocimetry Using Laser Scanning Techniques", *Experiments in Fluids*, Vol. 14, pp. 181-192, 1993 (with C. Magness, J. Towfighi, O. Akin and T. Corcoran).

"Instantaneous Structure of Vortex Breakdown on a Delta Wing via Particle Image Velocimetry", *AIAA Journal*, Vol. 31, No. 6, pp. 1160-1162, 1993 (with J. Towfighi).

## **PARTICIPANTS**

Participants in this research program have been:

Peter Vorobieff	Ph.D. Candidate (Anticipated completion: end of 1996)
Kimberly Cipolla	Ph.D. Candidate (Anticipated completion; mid-year 1996)
Robert Doherty	B.S. and M.S. Candidate (B.S. in Mechanical Engineering completed January, 1995)
J.-C. Lin	Research Associate

## 5. EXTERNAL INTERACTIONS

During the course of this program, our group has interacted with colleagues at Wright-Patterson Air Force Base. Assessment of the instantaneous flow structure on wings in transient motion, involving interactive comparison of experimental results obtained using particle image velocimetry and direct numerical simulations obtained at WPAFB, have allowed identification and definition of crucial features of the flow structure, including vortex breakdown, vortex topology, and critical states of the flow during a maneuver. These interactions have involved communication with Drs. M. Visbal, R. Gordnier and J. Shang.

In addition, discussions on the quantitative flow topology, corresponding to critical states of rolling moments measured in SARL wind tunnel tests, have involved communication with Drs. J. Jenkins and A. Hsia.

Finally, from a practical perspective, concepts of control of flow on complex wing configurations, including wings having a FLAK planform have involved communication with Mr. R. Osborn and Dr. W. Blake.