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Low Speed Aerodynamics of the X-38 CRV: Summary of Research NAG9-927,5/97-4/98

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1.0 SUMMARY REPORT

This project was performed in support of the engineering development of the NASA X-38 Crew Return Vehicle system. Wind tunnel experiments were used to visualize various aerodynamic phenomena encountered by the Crew Return Vehicle (CRV) during the final stages of descent and landing. Scale models of the CRV were used to visualize vortex structures above and below the vehicle, and in its wake, and to quantify their trajectories. The effect of flaperon deflection on these structures was studied. The structure and dynamics of the CRV's wake during the drag parachute deployment stage were measured. Regions of high vorticity were identified using surveys conducted in several planes using a vortex meter. Periodic shedding of the vortex sheets from the sides of the CRV was observed using laser sheet videography as the CRV reached high angles of attack during the quasi-steady pitch-up prior to parafoil deployment. Using spectral analysis of hot-film anemometer data, the Strouhal number of these wake fluctuations was found to be 0.14 based on the model span. Phenomena encountered in flight test during parafoil operation were captured in scale-model tests, and a video photogrammetry technique was implemented to obtain parafoil surface shapes during flight in the tunnel. Forces on the parafoil were resolved using tension gages on individual lines. The temporal evolution of the phenomenon of leading edge collapse was captured. Laser velocimetry was used to demonstrate measurement of the porosity of the parafoil surface. From these measurements, several physical explanations have been developed for phenomena observed at various stages of the X-38 development program. Quantitative measurement capabilities have also been demonstrated for continued refinement of the aerodynamic technologies employed in the X-38 project.

Detailed results from these studies are given in an AIAA Paper, two slide presentations, and other material which are given on a Web-based archival resource. This is the Digital Library of the Georgia Tech Experimental Aerodynamics Group, and can be found at:

http: //www.ae.gatech.edu/research/windtunnel/index.html

In this report, the contents of the Web Page are summarized:

2.0 Lifting-Body Aerodynamic Phenomena

Low-speed flow visualization was conducted over stereolithographic scale models of the XCRV Versions 3.0, 8.1 and 8.2. Laser sheets were aligned in various planes to see vortex systems and streamline patterns. Generally, the light sheet and camera were kept fixed in relation to each other and the model traversed through the light sheet. Seeding was introduced from upstream using decomposing wax from electrically-heated wires. The video tapes were frame-coded to link each frame to the corresponding position of the light sheet in body coordinates. Qualitative summaries of the various vortical structures are sketched on the web page; quantitative trajectories of these structures were obtained by measuring the location of given features in digitized video frames and then converting the pixel coordinates to physical coordinates fixed to the model. These tests were performed without flaps initially, and then with flaperons deflected to various angles and at various model angle of attack. Quasi-steady variations in angle of attack were also performed to observe the displacement and interaction of the vortices over the aft portion of the body.

The primary new result was the confirmation of vortical structures on the underside of the body at low and negative angles of attack. The interaction of these structures with each other, with the upper-surface vortex system, and with the flaperons should explain some of the anomalous characteristics reported during maneuvering flight of the CRV at fairly low angles of attack. The anomalies were reported in wind tunnel measurements of stability characteristics in supersonic flow. It should be noted that in considering the separated flow which forms vortices on the lower side, and in the near wake, there are substantial similarities in the cross-flow behavior between the supersonic flow and the incompressible flow studied here. The observations made here are thus of qualitative significance.

3.0 Wake Studies

Following drop tests of the X-38 model from a B-52 aircraft, some studies were conducted of the wake of the CRV in the region where the drag chute deployed. The wake was first surveyed with light sheets at various orientations. These tests showed the generation of a pattern similar to a Karman Vortex Street in the wake. A vortex meter was moved to various stations in the wake and the vorticity field was surveyed.

Following these, a survey was conducted with hot-film anemometer probes in several cross-flow planes in the wake. This showed the wake being convected down with respect to the model-fixed frame of reference (as expected because the model still generates some lift at high angles of attack). In the actual flight test video, it must be remembered that the model is rapidly falling, and so the wake with the vorticity concentrations will be somewhat above the model in an earth-fixed coordinate sysem when the parachute deploys.

The wake studies were done at low angles of attack, 30 degrees, 60 degrees and 90 degrees angle of attack. The hot-film data were analyzed using standard spectral analysis techniques. It was found that:

- The vortex shedding was clearly present at higher speeds as well.

- In most cross-flow planes, the spectrum of the hot-film signal exhibited clear peaks.
- The frequency of the dominant peak scaled linearly with tunnel speed.
- The Strouhal number (St = fL/U) was 0.14, where U was tunnel speed and L the span of the model.

From the flight test videotape, using rough guesses of the speed of the X-38 model, this Strouhal number would yield parachute bufffeting frequencies similar to those observed.

4.0 Parafoil Aerodynamics

An AIAA Paper presented at the Aerospace Sciences Meeting at Reno in January 1998 is attached in Appendix 8, and is available in .pdf form on the Web Page. This paper, and the presentation given on the Web Page, address the following issues:

- Parafoil operation in a wind tunnel under steady conditions
- Dynamic stalling processes due to separation over the leading edge
- Measurement of the surface shape of a parafoil at various spanwise stations using video photogrammetry.
- Extension of the photogrammetry technique to instantaneous surface shape measurement.
- Measurement of forces and moments on the parafoil using simultaneous measurement of tensions and orientations of several lines using strain gages.
- Measurement of porosity of the parafoil using laser velocimetry, and confirmation of porosity by illuminating seeded flows through the parafoil fabric.
- Capture of the detailed sequence of the leading-edge collapse phenomenon
- Demonstration that the parafoil will self-stabilize if taken to high angle of attack in a quasi-steady maneuver.

Some results to consider are:

- Dynamic stalling processes due to leading-edge upper surface separation. While these lead to unsteadiness, they did not cause collapse of the parafoil at high angle of attack in quasi-steady operation with the short lines that we used.
- Leading-edge collapse occurs when the upper-surface goes to negative angle of attack: even -3 degrees is adequate to start the process.
- High-angle-of-attack *collapse* may be a transient phenomenon, as follows:

1) Angle of attack increases due to control input.

2) Lift increases, imposing a sharp increase in tension on the lines holding the load.

3) There is a finite time delay for the tension to propagate along the lines, before the load experiences deceleration. During this time the parafoil descends at the same rate as before.

4) Lines go slack. When this wave reaches the parafoil, the lower surface goes slack, perhaps curling up at the leading edge, shifting the stagnation point to the lower surface.

5) Leading-edge opening closes, deflating the parafoil.

This hypothesis must be presented untested at this stage, but appears reasonable from observations of video, and from the fact that we were unable to reproduce high-angle-of-attack collapse in quasi-steady operation with short lines.

5.0 Air Data Probe Calibration

A short-term wind tunnel tests was conducted to calibrate the Air Data Probe used for the CRV. The data from these are posted on the Web, and can be found by going to the address specified on the first page.

6.0 Acknowledgements

This work was performed with the enthusiastic participation of several students of the Experimental Aerodynamics Group, and members of the engineering team from Johnson Space Center. The authors are most grateful for the opportunity to work with these teams

7.0 Appendix I: Degrees Supported

The following team members obtained / are approaching degrees, after gaining some of their experience on this project:

1. Richard G. Ames is completing his dual-Master of Science in Aerospace Engineering and Management degrees. His work was substantially supported under this project.

2. Liliana Villareal completed her MSAE degree in December 1997.

3. Hillary Latham completed her BAE degree in June 1998.

4. Oliver Wong received his MS degree in December 1997.

5. Clay Harden completed his BAE degree in September 1997.

6. Brian Gialloreto will complete his BAE degree in September 1998.

Other Undergraduate Participants: Antonio Abad, Jennifer Hoover.

8.0 Appendix II: Papers Published