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Engineering Notes

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Buffet-Induced Structural/Flight-Control System Interaction of the X-29A Aircraft

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Introduction

THE trend of today's aircraft design is toward more flexible, structurally efficient aircraft with high-gain flight-control systems. This trend has led to increasing occurrences of the flight-control system dynamics interacting with the aeroelastic response of the aircraft and the emergence of a discipline called aeroservoelasticity.[1] These interactions involve the unsteady aerodynamics, flight-control system, and structural dynamics of an aircraft. In mild cases, these interactions can increase dynamic loads on the flight-control surfaces, cause additional fatigue cycles on critical structures, or lead to unforeseen flight-control system anomalies. In more severe cases, these aeroservoelastic interactions can lead to a limited amplitude oscillation or an aeroservoelastic instability.

The X-29A forward-swept wing aircraft uses a high-gain digital flight-control system. A flight-test program at the NASA Dryden Flight Research Facility explored the high angle-of-attack flight regime. The high angle-of-attack flight-control laws contain modifications for flights above 10-deg angle of attack.[2] During flight envelope expansion up through 45-deg angle of attack, an aeroservoelastic interaction was observed between the buffet on the aircraft, the structural mode response, and the flight-control system in the lateral-directional axis. The small motion of the control surfaces caused by the aeroservoelastic interaction did not sustain or cause a limited amplitude oscillation. On the other hand, this interaction played a part in the control surface actuator commands miscomparing in the hydraulic logic of the flaperon actuator during high-speed maneuvers. This miscomparison resulted in the flaperon actuator reconfiguration during flight. The actuator reconfiguration resulted in an increase in flight-test time because of requirements for repeat flight maneuvers. In addition, this reconfiguration was one of the catalysts for control law and hardware design changes in the flight-control system.

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Flight Conditions and Discussion of the Interaction

The analyzed flight conditions were 1-*g* flight envelope expansion test points for angles of attack from 10 to 45 deg. The entry speed for the high angle-of-attack maneuvers was between 120–140 kt equivalent airspeed. Entry altitude was 38,000 ft with an altitude loss of 5000–13,000 ft occurring during the test maneuver. The minimum recovery altitude was 25,000 ft. The flight-control feedback gains were primarily a function of dynamic pressure and angle of attack which remained relatively constant during the maneuvers.

During high angle-of-attack flight maneuvers, the aircraft structure was being excited by the forebody vortices impinging on the vertical stabilizer. The wing also experienced separated flow for angles of attack greater than 15 deg, which added to the excitation. This excitation will be referred to as buffet.

The aerodynamic buffet excited the structural modes of the aircraft at 11, 13, and 16 Hz, thereby causing signals at these frequencies to be measured by the roll rate and yaw rate gyros. Rate gyro output signals were then amplified through the flight-control laws and sent to the flaperons and rudder as additional commands. The following subsections describe each aspect of the interaction. Data used are from selected structural accelerometers and feedback sensors. Power spectral densities shown are at an angle of attack of 30 deg, which was the angle of attack at which the buffet amplitudes peaked and started to level off.

Structural Response of the Aircraft

Figure 1 shows a power spectral density of the rudder trailing-edge structural accelerometer signal at 30-deg angle of attack. There are three major structural response frequencies in the data. The first two are 11 and 13 Hz, and their response levels are approximately one order of magnitude greater than the noise floor. The third peak is at 16 Hz with a response level two orders of magnitude greater than the noise floor. By adding and subtracting flight accelerometer data and reviewing the ground vibration test results of the X-29A,[3] the 11-Hz mode was identified as antisymmetric wing bending, the 13-Hz mode as fuselage lateral bending, and the 16-Hz mode as vertical stabilizer bending. These structural frequencies were also observed in the data from other structural accelerometers on the aircraft.

Flight-Control System and Sensor Feedback

The power spectral densities of the rate gyro outputs (Fig. 2) showed a high-amplitude roll rate feedback between 10–

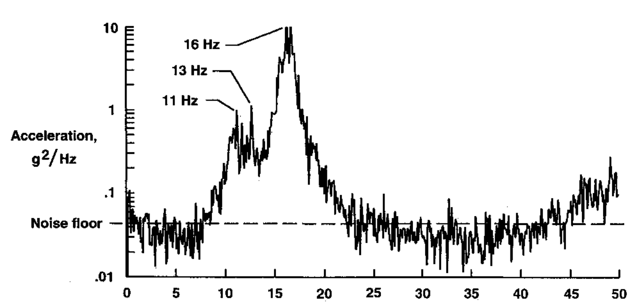

Fig. 1 Power spectral densities of rudder accelerometer.

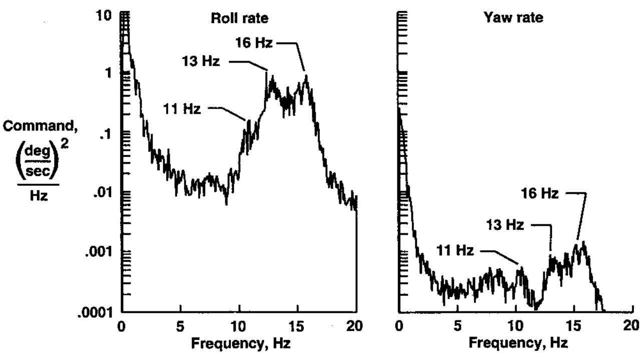

Fig. 2 Power spectral densities of roll rate and yaw rate feedback sensor.

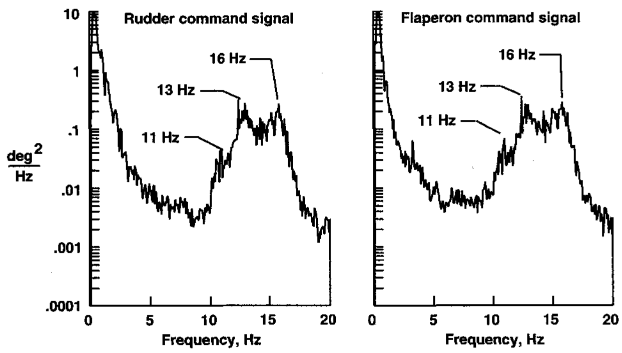

Fig. 3 Power spectral densities of rudder and flaperon actuator commands.

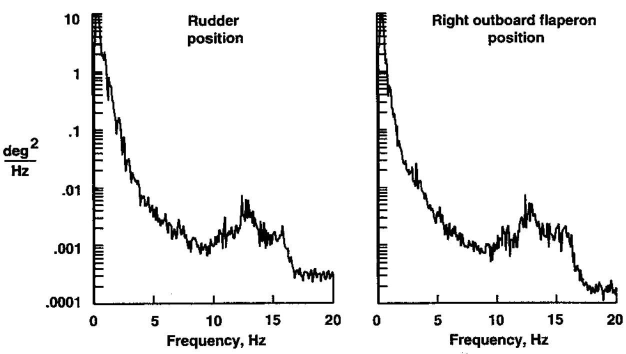

Fig. 4 Power spectrums of rudder and flaperon positions.

20 Hz, with the structural response peaks at 11, 13, and 16 Hz. The yaw rate signal over the same frequency band and flight conditions was approximately three orders of magnitude less, and does not appear to be significant, which may be partially attributed to the structural notch filter at 11.2 Hz in the yaw rate path.

Control Surface Actuator Command

The high-amplitude roll rate feedback signal was now being commanded to the rudder and flaperon surfaces by the flight-control system. Figure 3 shows the power spectral densities of the flight-control computer commands to the rudder and flaperon channels. Rudder and flaperon command and roll rate signal power spectral densities (Fig. 2) showed similar frequency content. The structural resonant frequencies at 11, 13, and 16 Hz were apparent.

Rudder and Flaperon Actuators

Roll-off characteristics of the rudder and flaperon actuators, coupled with the rotational inertias of the control surfaces, tend to attenuate much of the actual control surface response at the high frequencies. The power spectral densities of the rudder and outboard flaperon position, shown in Fig. 4, still retained control surface response to the high-frequency commands between 10–20 Hz. The resonant frequencies at 11, 13, and 16 Hz were again apparent. Relative amplitude of the position signal was approximately two orders of magnitude less than the amplitude of the commanded signals in this frequency band (Fig. 3). At and above 30-deg angle of attack, the rudder and flaperon displacement varied from ± 0.2 to ± 0.4 deg.

Consequences of the Interaction

Although this interaction did not produce an instability, an adverse effect occurred during maneuvers while the aircraft was flying at or above 30-deg angle of attack. The flaperon servoactuator was reconfigured because of a miscomparison in the hydraulic logic of the actuator. As a result, a servoactuator failure-annunciator light was illuminated during the flight-test point.

The high-amplitude roll rate signal commands in the 10- to 20-Hz frequency range may have caused the servoactuator reconfiguration. These high-frequency commands were outside the response capability of the actuator. The first servoactuator reconfiguration caused the flight test to be terminated. In later flights, the actuators were reset in-flight, and the test point was repeated until it was successfully flown without a servoactuator reconfiguration. The long-term effects of the commanded high-frequency signals on the actuators are unknown.

A notch filter was designed and implemented for the roll rate gyro path of the flight-control system. The simple notch filter had a notch frequency of 16 Hz. The denominator was critically damped (0.707 damping ratio), and the numerator was damped one-tenth of the denominator (0.0707 damping ratio).

Concluding Remarks

An aeroservoelastic interaction was observed in the lateral-directional axis of the flight-control system during the high angle-of-attack flight envelope expansion of the X-29A forward-swept wing aircraft. The interaction consisted of three structural modes at 11, 13, and 16 Hz. These modes were excited by high buffet levels, passed through to the flight-control system by the feedback sensors, and resulted in commands to the control surface actuators. A small magnitude aerodynamic excitation was induced by the control surface movement. The effects of this excitation were washed out by the high level of buffet excitation on the aircraft. The roll-off characteristics of the actuator system of the X-29A prevented this aeroservoelastic interaction from becoming a limited oscillation or an aeroservoelastic instability.

The control surface actuators could not fully respond to the high-frequency commands induced by the aeroservoelastic interaction. These commands contributed to a flaperon actuator reconfiguration because of a miscomparison in the logic of the actuator. This servoactuator reconfiguration resulted in an increase of flight test time and maneuvers to clear the desired high angle-of-attack flight envelope safely. These aeroservoelastic interactions were catalysts for changes in the flight-control system. These changes included the addition of a notch filter to the roll rate gyro path. The notch filter eliminated all reconfigurations in the actuators except those for extreme high-speed and high angle-of-attack maneuvers.

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Boundary-Layer Influences on the Subsonic Near-Wake of Bluff Bodies

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Introduction

MUCH attention has been given to the subject of subsonic axisymmetric bluff body wakes, however, data on nonaxisymmetric flows seem relatively sparse.[1] Previous analytical and experimental studies of bluff body flows have revealed a relationship between near-wake parameters and the state of the incoming boundary layer in both the subsonic and supersonic regimes; however, only a limited number of studies have detailed the relationship in depth, and then only for axisymmetric bluff bodies.[2,3]

A bluff body geometry of particular interest is the slanted-base, ogive-cylinder geometry which has been tested by Morel[4] and others.[5–7] The interest in this geometry is the sudden change of wake structure, with corresponding large change in drag coefficient, occurring for small changes of base slant angle, around 45 deg. The two wake types are a quasisymmetric, turbulent closure at low slant angles (blunt base), and a longitudinal vortex flow at high slant angles (slender base), as illustrated in Fig. 1.

Experimental Details

The model used in this study comprised a streamlined nosepiece with interchangeable centerbody and base components, covering a range of slant angles ("low" slant angles of 0, 40, 45 deg, and a "high" slant angle of 50 deg). The centerbody was slightly tapered (0.3-deg half-angle) with the intent of delaying boundary-layer transition to a higher Reynolds number. The length-to-base-diameter ratio (L/D) of all models is 6, measured to the most upstream point of the base. Experiments were conducted in a 4- × 3-ft, atmospheric, low-speed wind tunnel with the model mounted on a swept, slender strut attached to the nosepiece. Boundary corrections were not necessary since the model-to-test section area ratio was less than 1%. During some tests the forebody boundary layer was modified by fixing transition at one of three locations, at the leading edge, center, and near the trailing edge of the centerbody.

Experimental Results

Boundary-Layer Measurements

Boundary-layer characteristics were measured at a location 0.2-base diameters ahead of the most upstream point of the base. Boundary-layer profiles closely corresponded to classical laminar or turbulent forms. Typical momentum thicknesses, determined by integration, are shown in Fig. 2. It is thought that boundary-layer tripping did not occur at the lower Reynolds numbers, due to too small a grit size, but that natural transition reached the upstream end of the centerbody at higher Reynolds numbers.

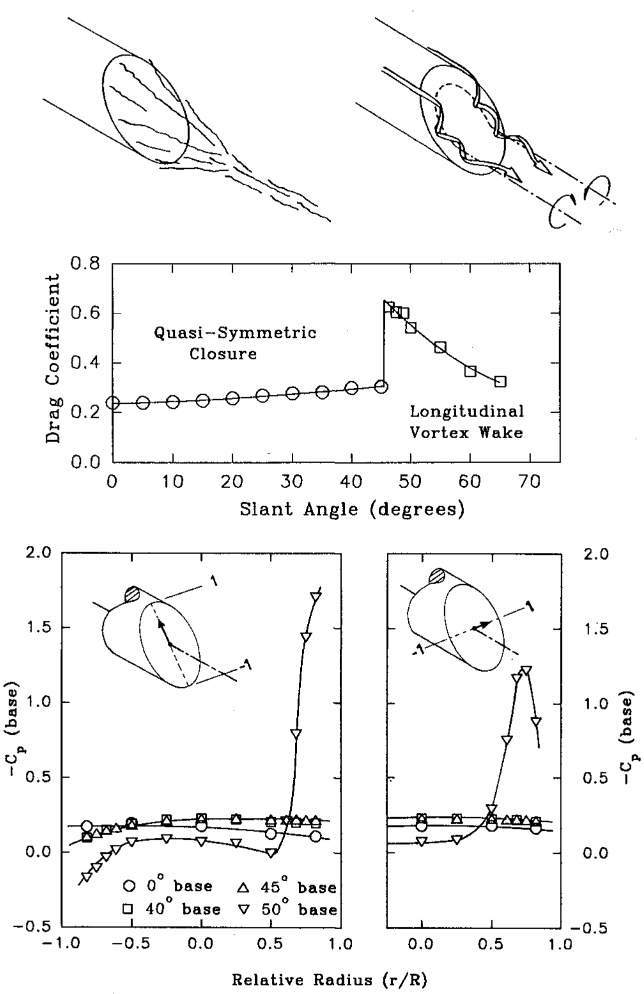

Fig. 1 Typical wake structures, drag variation, and base pressure distributions.

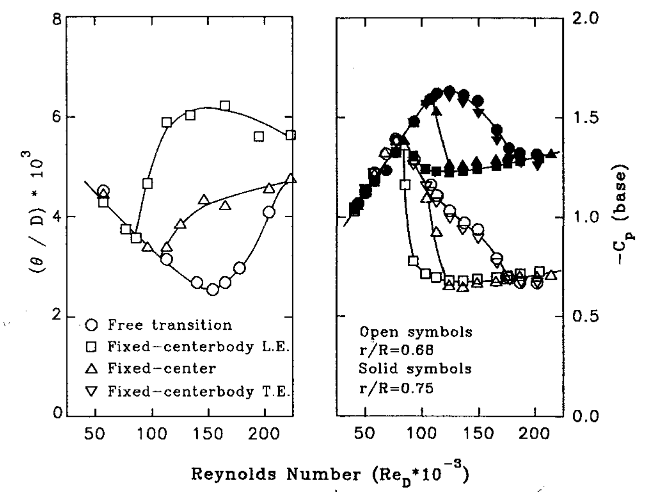

Fig. 2 Boundary-layer thickness and selected base pressures, 50-deg base.

Base Pressure Measurements

The general form of the base pressure distributions for the two types of wake flow were shown in Fig. 1. Base pressures

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