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Engineering Notes

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Digital Flutter Suppression of Active Flexible Wing Using Moment Feedback

Martin J. Klepl*
Rockwell International, El Segundo, California 90009

Introduction

FLUTTER suppression system (FSS) control laws were to be designed for the active flexible wing (AFW) technology wind-tunnel model. The FSS requirement was to develop low-order robust digital flutter suppression control laws that would suppress symmetric and antisymmetric flutter. Flutter is required to be suppressed while maintaining stability over the entire test dynamic pressure range and maintaining stability margins of ±4-dB gain and ±30-deg phase. These requirements must be satisfied while allowing acceptable control activity. For a feasibility exploration, the feedback sensor is to be a wing-bending moment or wing-torsion moment strain gauge. One significant goal of the wind-tunnel test is to perform high-speed wing-load reducing roll maneuvers beyond the flutter speed while suppressing the symmetric flutter mode.

Wind-Tunnel Model

As part of Rockwell International's work in AFW technology, a one-sixth scale model of the forebody with wings was built for wind-tunnel testing. The model has already been in the wind tunnel three times before entry in March 1991. The wings are aeroelastically scaled to flutter at a dynamic pressure of 230 psf.

Reference 1 and other articles in this special AFW issue describe the AFW wind-tunnel model. The flutter suppression system uses bending and torsion moments as the wing feedback-sensor instead of the universally applied accelerometer. The strain-gauge moment sensors were limited to those already on the wings because none were planned to be added. The sensors were located at wing root (inboard) and wing midspan (outboard). The four available control surfaces on each wing were the leading-edge inboard (LEI), leading-edge outboard (LEO), trailing-edge inboard (TEI), and trailing-edge outboard (TEO). The LEI was not permitted for use, and the LEO was not used for model safety. The two trailing-edge control surfaces were used by the flutter suppression control laws.

Mathematical Representation of the Model

The mathematical representation of the wind-tunnel models was provided as 10 symmetric flexible modes and 10 antisymmetric flexible modes. For these two flexible-vehicle models, the full unsteady frequency domain aerodynamics were analytically curve-fit with four aerodynamic lags.[2] This approximation to the unsteady aerodynamics allows state-space formulation of the model and subsequent digital control law design. These analytical models included a full complement of 20 models: four different dynamic pressures and five configurations. The four dynamic pressures were: 150, 200, 250, and 300 psf. The five configurations were 1) symmetric (the same whether roll brake is on or off), 2) antisymmetric with roll brake on, 3) antisymmetric with roll brake off, 4) total vehicle with roll brake off, and 5) total vehicle with roll brake on. The model has a 10-Hz symmetric flutter mode whether the roll brake is "on" or "off," but the antisymmetrical model has a 10-Hz flutter mode only with the roll brake on. Consequently, only the symmetric flutter suppression system needed to be engaged during roll maneuvers (roll brake off).

Flutter Suppression Control Laws

Flutter suppression control laws were designed independently for both the symmetric flutter suppression system and the antisymmetric flutter suppression system. The design method was direct digital design in the frequency domain to satisfy the Nyquist criterion. The controller sample rate was 200 samples/s. The digital computer implementation of the control law adds about 27 deg of phase lag at the flutter frequency: 9 deg for the zero-order hold data reconstruction, and 18 deg for the full sample delay within the computer. This delay was verified from special tests performed on the wind-tunnel digital computer to determine the phase lag. Because the uncertainties were expected to be in phase, rather than gain, emphasis was placed on achieving phase margin even at the expense of gain margin. Resulting stability margins are shown in Table 1.

Transonic Dynamics Tunnel Testing

The AFW technology wind-tunnel model was tested in the NASA Langley Transonic Dynamic Tunnel (TDT) during March 1991. To ensure the safety of the wind-tunnel model, closed-loop testing proceeded by turning the flutter suppression system on at a dynamic pressure of 100 psf and increasing dynamic pressure slowly through flutter (235) to 290 psf (the maximum capability of the TDT when air is used as the test medium). With the roll brake off, the symmetric flutter mode was suppressed throughout the dynamic pressure range up to a dynamic pressure 23% above the flutter dynamic pressure. Table 2 shows the TEI control surface performance during this flutter suppression. The rms position is less than 0.25 of a degree, and the rms rate is less than 15 deg/s. The conclusion is that the FSS does not appreciably reduce the control authority of the other control systems.

Additional wind-tunnel tests involved rolling the model using the roll rate tracking system (RRTS) to reduce wing loads through 90-deg bank angle while suppressing flutter with the FSS at increasing roll rates. Under these conditions, the symmetric flutter system was engaged as well as the RRTS. The significant result of this whole test was that the model rolled 90 deg within 0.5 s (to meet MIL-SPEC) at a dynamic pressure

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*Engineering Specialist, North American Aircraft Division. Member AIAA.

Table 1 AFW technology flutter suppression system wind-tunnel model digital control loop stability margins

Control loop (at actuator)	Dynamic pressure, psf	
	300	250
Symmetric	-4 dB $\leq$ Gain $\leq$ 4 dB	-13 dB $\leq$ Gain $\leq$ 8 dB
	-35 deg $\leq$ Phase $\leq$ 32°	-70 deg $\leq$ Phase $\leq$ 60°
Antisymmetric brake on	-3.3 dB $\leq$ Gain $\leq$ 3.3 dB	-7.5 dB $\leq$ Gain $\leq$ 7.5 dB
	-26 deg $\leq$ Phase $\leq$ 24°	-32 deg $\leq$ Phase $\leq$ 70°

Table 2 AFW technology flutter suppression system TEI control surface performance during brake-off March 1991 wind-tunnel test results

Dynamic pressure, psf	rms position, deg	rms rate, deg/s	Maximum position, deg	Maximum rate, deg/s
200	0.12	6.97	0.52	33.85
250	0.18	10.91	0.82	52.08
265	0.19	11.56	0.81	46.88
275	0.20	12.27	0.79	49.48
290	0.23	14.23	0.86	57.29

(260) 11% beyond flutter speed. In addition, the roll trim system (RTS) rolled the model at 290 psf (which was 23% beyond flutter speed).

Conclusions

FSS control laws were designed and tested for the AFW technology wind-tunnel model. The design approach was to use torsion moment strain gauges and bending moment strain gauges as the feedback sensors instead of the standard accelerometers. The synthesis method was the classical single-input/single-output using direct digital design in the frequency domain applying the Nyquist criterion. The model entered the TDT at NASA Langley Research Center during March 1991 for testing. The significant results of the wind-tunnel test are that both the symmetric and the antisymmetric flutter modes were successfully stabilized at 23% beyond flutter speed, and that the symmetric flutter mode was successfully stabilized at 11% beyond flutter speed during high roll rate maneuvers through 90 deg and 23% beyond flutter speed during low rate roll trim maneuvers. The control authority of the FSS did not interfere with either the RRTS or the RTS during the wind-tunnel tests. The conclusion that bending moments and torsion moments are good candidates for feedback sensors in FSS is supported by these results. Future study of the application of these sensors in FSS should include sensor location and control law design methods to take advantage of these sensors.

Acknowledgments

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Maneuver Load Control Using Optimized Feedforward Commands

Doug Moore*
Rockwell International Corporation, Los Angeles, California 90009

Introduction

A MANEUVER load control (MLC) system has been designed for and tested on the active flexible wing (AFW) wind-tunnel model.[1] The MLC system was designed to constrain wing bending and torsion loads, while maintaining roll performance. Successful MLC systems will allow designers additional options in the aerodynamic and structural design of wings. The objectives of this work were to provide design and test experience in MLC systems and in the integration of MLC systems with flutter suppression systems.

Control Law Design

The method used for the MLC design was to treat the roll-load situation as a constrained optimization problem. Simplifying assumptions included treating the wind-tunnel model as a rigid body and neglecting load feedback. From previously obtained wind-tunnel data of wing loads and model response due to surface deflection, a multidimensional gradient problem was formulated that maximized roll performance without exceeding load limits. The optimization procedure minimized total control-surface deflection while producing required roll acceleration and roll rate without exceeding wing loads or control-surface deflection constraints. Optimization proceeds until conflicting load and/or deflection constraints exist; this defines the maximum possible roll performance subject to the design constraints. The final product of this design method was a set of look-up tables of control-surface deflection as functions of roll rate and roll rate error. The purpose of the MLC portion of the AFW wind-tunnel test was to evaluate the performance of the look-up tables generated by the optimization algorithms.

Test Results

Testing on the AFW wind-tunnel model in the NASA Langley Transonic Dynamics Tunnel confirmed the concept of optimized feedforward commands as a basis for an MLC system. Projected roll rates of 300 deg/s were achieved with reductions in torsion and bending moments (compared to tests conducted without the MLC system at the same high roll rates).

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*Member Technical Staff, Vehicle Dynamics and Control, North American Aircraft Division, P.O. Box 92098.