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Active Flutter Suppression on an F-4F Aircraft

O. Sensburg* and H. Hönlinger†
Messerschmitt-Bölkow-Blohm, West Germany
and
T.E. Noll‡ and L.J. Huttsell‡
Air Force Wright Aeronautical Laboratories, Wright Patterson Air Force Base, Ohio

Extensive research programs have been conducted at Messerschmitt-Bölkow-Blohm (MBB) to investigate the application of active flutter and mode control to achieve increased flutter margins. Such techniques are of special interest for airplanes that already have a full command and stability augmentation system together with fast responding control surface actuators and that carry heavy wing mounted stores. A flutter suppression system (FSS) was installed on the F-4F, and this system was flight tested. The control law was found by applying optimal control theory, thus minimizing the control surface motion due to disturbances and providing the required stability margins. During the test it was found that the dynamic properties of the wing-pylon-store system change considerably with vibration amplitude because of play and preload.

Introduction

In recent years MBB has conducted many studies and development programs accompanied by wind-tunnel and full-scale airplane tests in the field of active flutter and elastic mode suppression. A successful wind-tunnel test was conducted in 1975 with a dynamically scaled model of a fighter airplane, suppressing wing store flutter with store mounted vanes.[1] Surface flutter speed was increased on a fintail plane-aft fuselage with a hydraulically driven rudder.[2,3] Miniature model actuators and new wind-tunnel test techniques were developed to investigate FSS with flutter models. Special computer programs—utilizing the optimal control theory[4]—were adapted to find suitable control laws for flutter suppression. A very successful application of these programs is described in Ref. 5. Analytical development of systems to reduce buffet induced pilot vibrations was presented in Ref. 6. A system to improve the ride comfort of a low-wing loaded fighter was detailed recently.[7] Two full-scale airplanes were equipped and flight tested to prove the feasibility of active flutter suppression. The first test was performed with a Fiat G 91/T3 which used additional control surfaces (vanes) to produce aerodynamic forces which counteract the store motion.[8]

In 1977, a much more challenging program was launched in cooperation with the Bundesamt für Wehrtechnik und Beschaffung (BWB) and the U.S. Air Force Flight Dynamics Laboratory. The program is described in this paper. The objective of this effort was to develop and flight test a system for flutter suppression which could become a possible candidate for an operational system. To generate the necessary unsteady control aerodynamic forces, existing control surfaces (ailerons) were used. Accelerometers located on the wing gave signals which were fed back through the existing stability augmentation system of the airplane.

As a flying test bed for this program, an F-4F aircraft of the German Air Force test center at Manching (Erprobungsstelle 61 der Bundeswehr) was chosen. This airplane was already equipped to perform flight flutter tests with stores. The program was jointly sponsored by the ZTL-Research Program of the German Ministry of Defense and by the U.S. Air Force.

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*Head of Structural Dynamics.

†Project Manager, F-4F Flutter Suppression Program.

‡Aerospace Engineer, Flight Dynamics Laboratory. Associate Fellow AIAA.

Selection of the Wing Mounted External Store Configuration

To determine a store configuration for demonstrating the FSS on the F-4F, a theoretical study[9] was used to determine store configurations that would flutter within the flight envelope. The full weight-inertia-c.g. range of given stores was not available to us because a safety system that will be explained later also had to be accommodated. Exotic c.g. positions, which may also cause low flutter speeds, were excluded for flight mechanical and load considerations.

A contour plot of flutter speeds for possible weight and radius of gyration combinations is depicted in Fig. 1. The selected store mass and the corresponding radius of gyration to achieve a low flutter speed is also shown in this figure.

The v-g plot for this critical store configuration is presented in Fig. 2. A safe configuration was also chosen from Fig. 1. This configuration could be realized by releasing two masses inside the store, thus changing the radius of gyration. Figure 3 shows the related damping trends and the increase of the flutter speed for the safe store configuration.

The validity of the dynamic properties of our mathematical model was proven by a ground resonance test (GRT). Good correlation between test and analysis was found, as can be seen from the comparison of the frequencies in Fig. 4; but it should be pointed out here that because large nonlinearities do exist in the pylon store attachment, this comparison is only valid for a distinct vibration amplitude.

The effect of pylon pitch stiffness on flutter speed is very pronounced (Fig. 5). This can be illustrated by the location of the nodal line on the wing (Fig. 6). As already shown in Ref. 10, there is a certain location of nodal line (approximately midwing chord) which gives the lowest flutter speed, and forward or aft locations increase this speed.

Both ground resonance (Fig. 7) and flight excitation tests show that the frequency of the store pitch mode is amplitude dependent. A possible explanation of this phenomenon can be found using linear approximations of the nonlinearities. If there is preload and backlash in the pitch axis of the store-pylon system, depending on the vibration amplitudes, we will get various pylon pitch stiffnesses which, in turn, lead to changes in the flutter speed. Because the flutter speed increases with the pylon pitch stiffness (Fig. 5), we will get amplitude limited flutter for the selected store configuration.

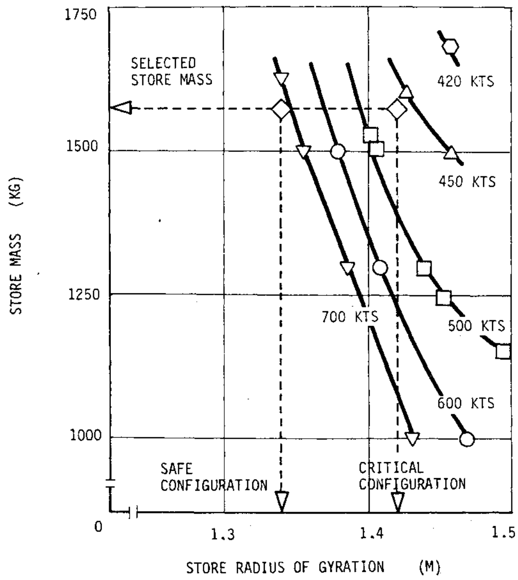

Fig. 1 Flutter speeds vs store mass and radius of gyration.

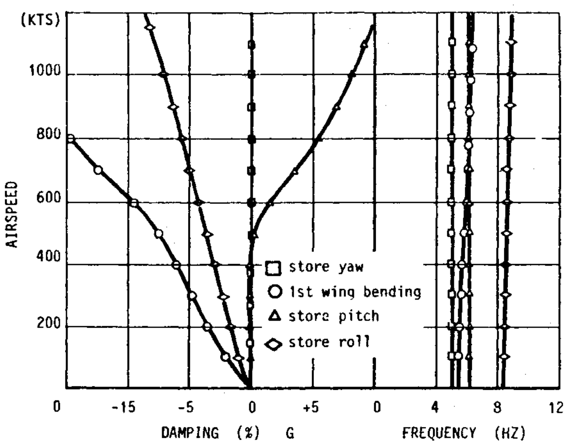

Fig. 2 Damping and frequency vs velocity.

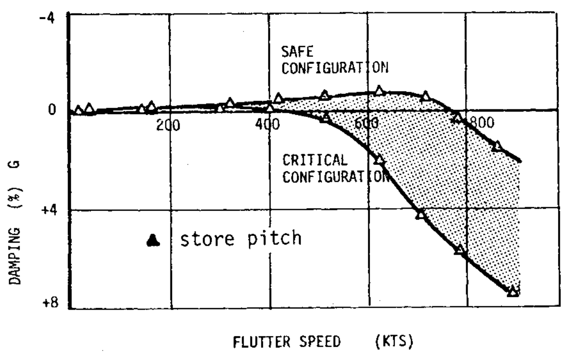

Fig. 3 Flutter behavior of the critical and safe store configuration.

MODE	GRT-RESULTS	ANALYSIS
1ST WING BENDING	5.63 HZ	5.46 HZ
STORE YAW	5.63 HZ	5.70 HZ
STORE PITCH	6.67 HZ	6.52 HZ
STORE ROLL	8.67 HZ	8.48 HZ

Fig. 4 Frequency comparison of GRT and analysis.

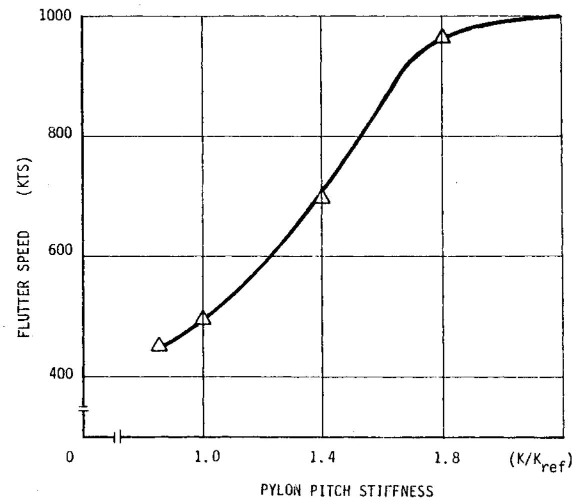

Fig. 5 Flutter speeds vs pylon pitch stiffness.

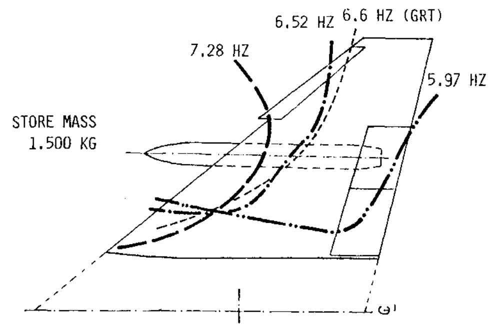

Fig. 6 Nodal line shift of the store pitch mode.

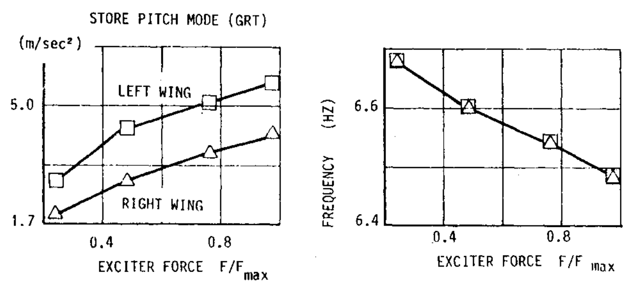

Fig. 7 GRT linearity check of the store pitch mode.

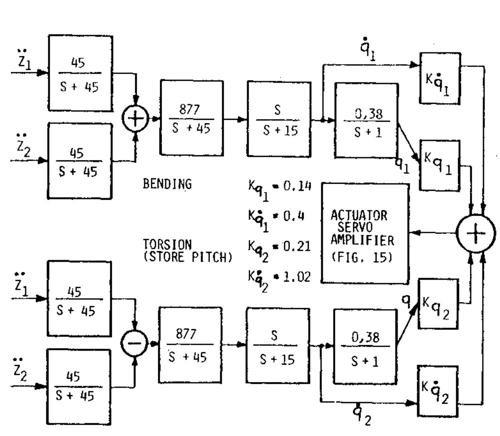

Fig. 8 Block diagram of the control law.

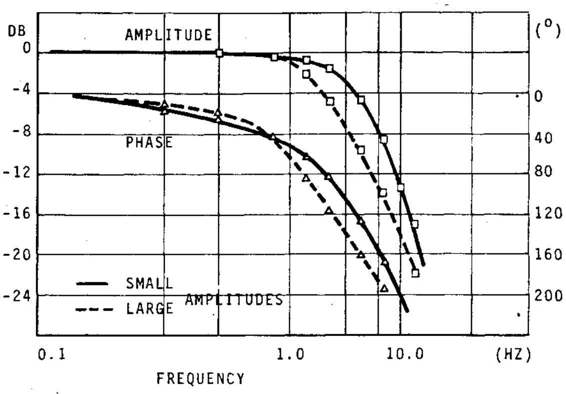

Fig. 9 Transfer function of the aileron actuating system.

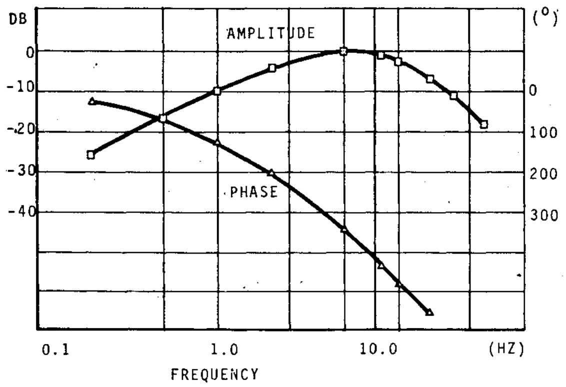

Fig. 10 Transfer function of the control electronics.

Using these linear approximations of the nonlinearities, the harmonic balance method can be applied and nonlinear flutter calculations can be made.[11]

Technical Approach for Finding the Control Law

A computer software system exists at MBB for application of optimal control theories to flutter and vibration suppression. The mathematical approach can be found in Ref. 8. Examples of active flutter suppression applications are found in Ref. 12 and Ref. 13.

The selected F-4F flutter case can be described by two modes: 1) first wing bending, q_1; 2) first wing torsion plus store pitch, q_2. These modes can be measured by two accelerometers on the wing. The block diagram of the control law is shown in Fig. 8.

Input Data and Analysis Results

As mentioned before, an approximated transfer function of the whole flutter suppression system had to be introduced into the mathematical model. The basis for this approximation was measured transfer functions of the subsystems. Figure 9 shows the transfer function of the complete aileron actuating system with a modified National Waterlift Power Actuator which gave better high frequency response than the standard actuator. The transfer function of the control electronics, with a bandpass filter included to avoid detrimental coupling of the FSS with rigid body modes, is depicted in Fig. 10.

The unsteady aerodynamic forces were calculated with the doublet lattice[14] and Laschka's[15] Lifting Surface Method. Approximations for these generalized aerodynamic forces are shown in Fig. 11, and this figure indicates that they are represented well. These approximations are necessary in order to calculate the optimal control law in the time domain.

Several control laws were optimized in the time domain at a design speed of 600 knots, using different quadratic performance criteria to minimize the control surface motion. A

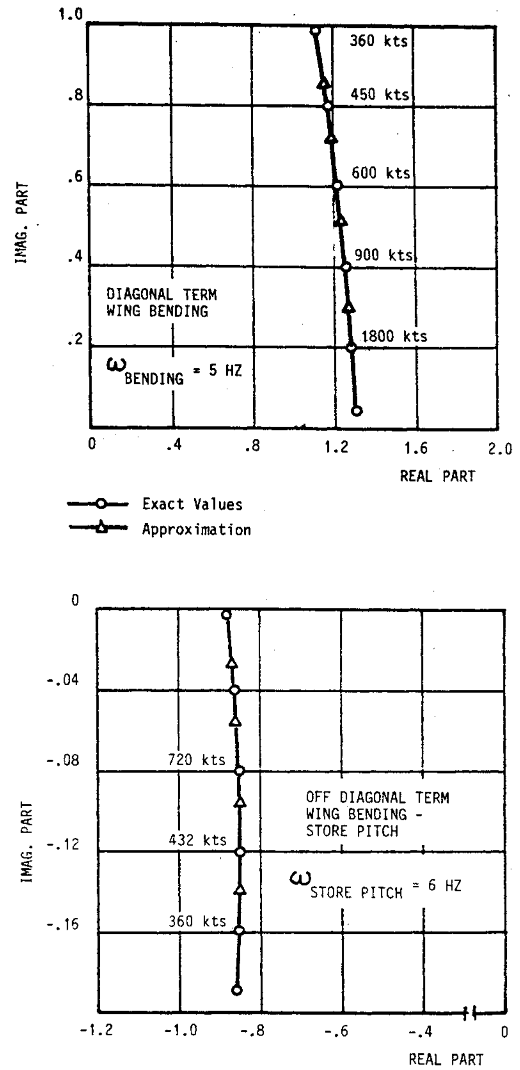

Fig. 11 Comparison of approximated generalized unsteady aerodynamic forces.

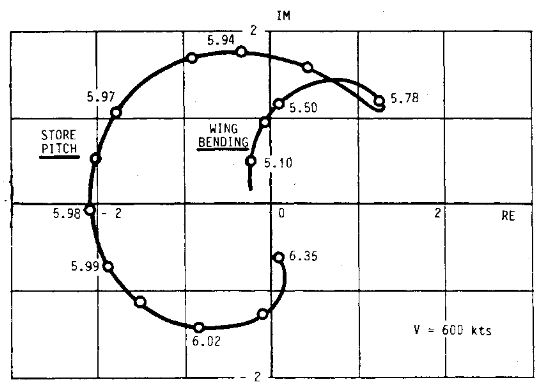

Fig. 12 Nyquist diagram of the F-4F with FSS.

Nyquist diagram for the selected control law is shown in Fig. 12. The critical point (−1) is encircled from the left side, and there is sufficient gain and phase margin at 600 knots. All control laws found were assumed to be valid in a wide range of off-design conditions. To check the selected control law over the whole flight envelope, a flutter calculation with the FSS was performed (Fig. 13). This figure shows an increase in flutter speed with the FSS of 200 knots for zero structural damping.

Implementation of the FSS into the F-4F Aircraft

Because the aircraft was already equipped for store flight flutter testing, only small modifications were necessary for the implementation of the FSS. Figure 14 shows a schematic view of the airplane with the feedback sensor locations, the modified aileron power actuators, the flight test equipment, and the FSS control box and panels.

The output of the FSS box was fed into the roll channel of the stability augmentation system as shown in Fig. 15. To avoid mechanical coupling of spoilers and ailerons, a static 2.5-deg-downward position of the ailerons (realized by a bias) was chosen.

Safety Requirements and Installations

For flight testing at supercritical speeds, a safety concept was developed together with the German government, Airworthiness Office ML (Ref. 16) and the AFFDL-Specialists. The block diagram in Fig. 16 explains the basic idea to achieve the necessary redundancy for this experimental program.

There are two FSS's working independently on each wing. Either one is able to suppress flutter up to a certain speed. If both systems fail, an automatic electrical system which responds to preselected amplitudes activates the mechanical flutter stopper of Fig. 17, which releases the trim weights in

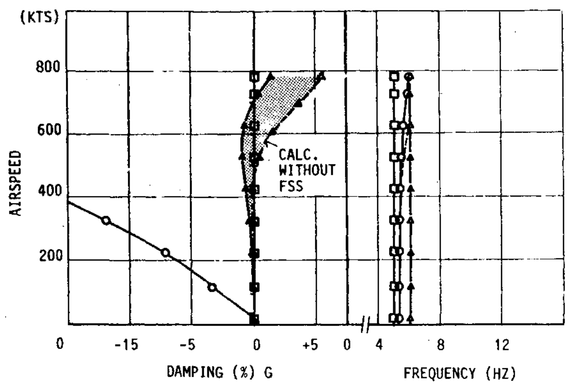

Fig. 13 Damping and frequency vs velocity for the F-4F with FSS.

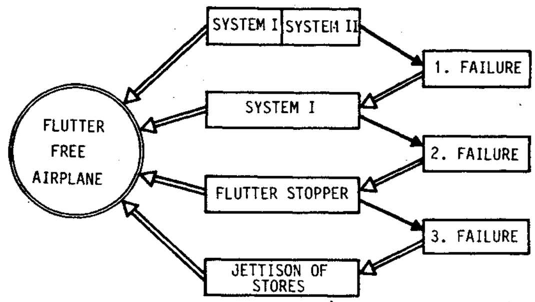

Fig. 16 Safety concept for the flight test program.

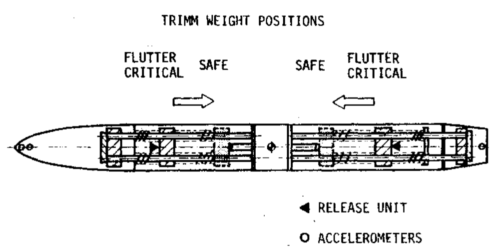

Fig. 17 Scheme of the flutter stopper.

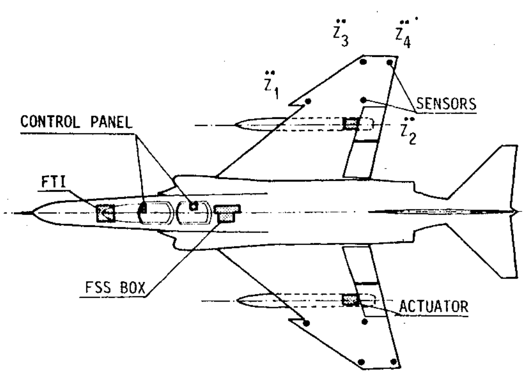

Fig. 14 Installation of the FSS and flight test instrumentation (FTI).

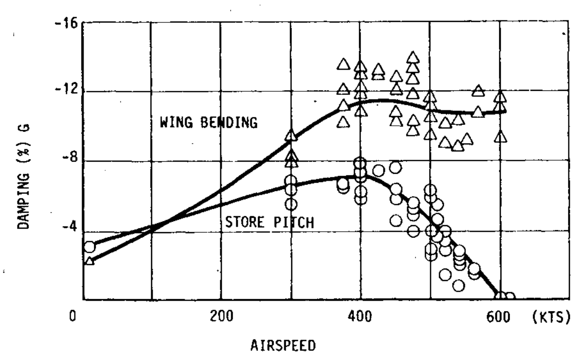

Fig. 18 Measured damping trend of the critical store configuration.

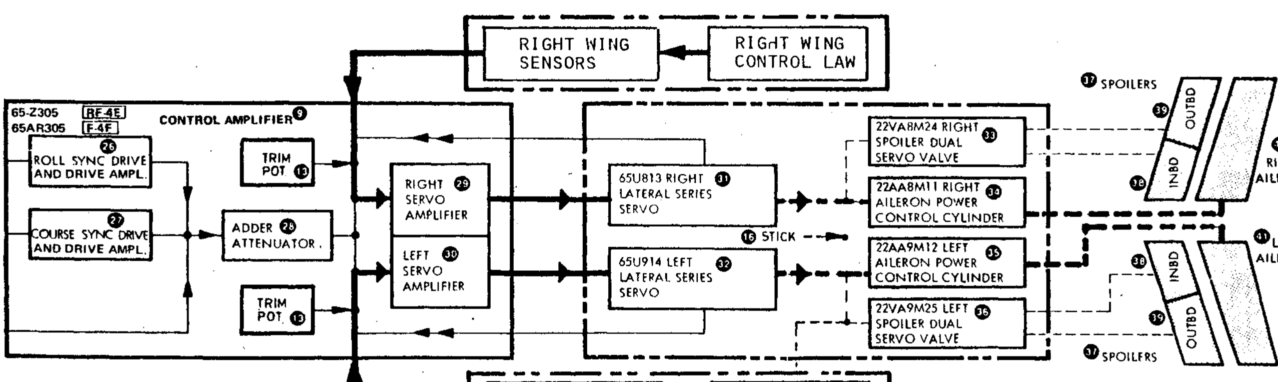

Fig. 15 Implementation of the FSS and the CSAS roll channel.

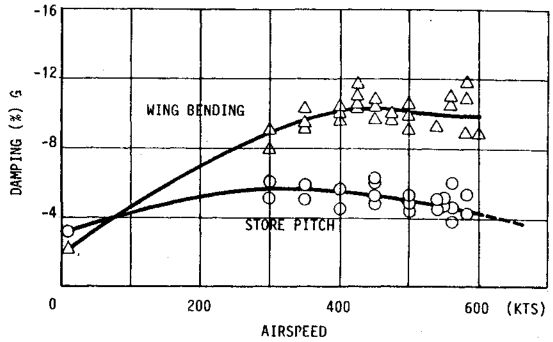

Fig. 19 Measured damping trend of the safe store configuration.

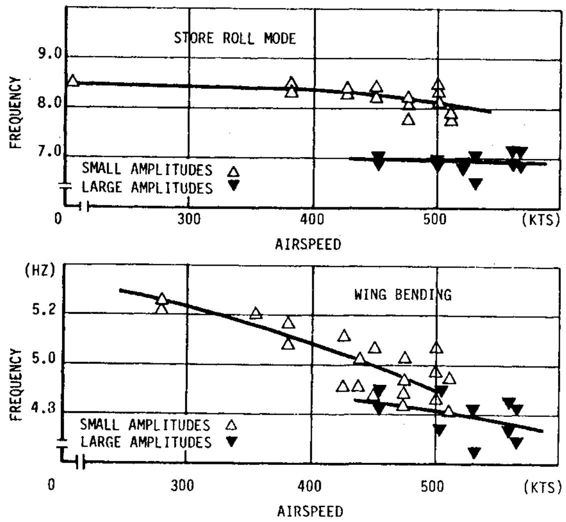

Fig. 20 Frequency spread due to structural nonlinearities.

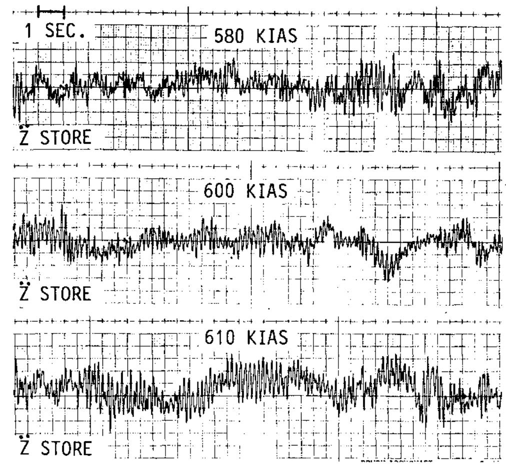

Fig. 21 Time histories at critical speeds.

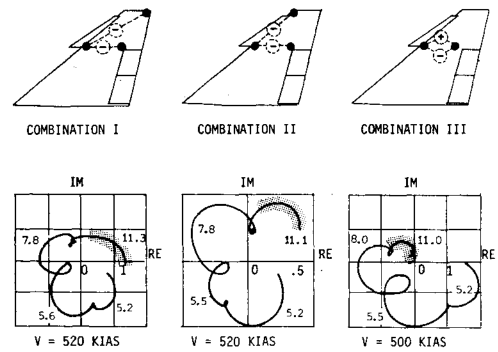

Fig. 22 Effect of sensor locations on Nyquist diagrams.

the store to create a flutter-safe radius of gyration. This is performed within 0.5 s, which means less than three flutter cycles. Both stores are designed as flutter stoppers and either one is able to suppress flutter, creating an asymmetric store combination. In the utmost critical case, the stores can be jettisoned by the pilot.

Ground Tests

All systems introduced for the FSS had to be qualified according to the requirements of the German Airworthiness Office ML, AFFDL, and MIL-Specifications.

An extensive structural mode coupling test was made in order to 1) check out the whole system with inertia forces and compare with calculated Nyquist plots for zero airspeed and 2) avoid adverse coupling with high frequency structural modes.

Flight Test Procedure

The flight test program for the FSS can be divided into three major sections: 1) classical flight flutter tests to find the flutter speed for the critical and safe store configuration; 2) open loop tests for substantiation and optimization of the analytically defined control law; and 3) closed loop tests to demonstrate flutter and mode suppression.

Classical Flight Flutter Tests

The airplane was excited with a frequency sweep input into the ailerons. The damping and frequency of the interesting modes was found by applying stochastic methods to get the transfer functions. ,The modes were separated by filter correlation. Hewlett Packard special computer 5451 B was used for this process, applying the MBB software. The methods used are described in Ref. 17.

Figure 18 shows a *v-g* plot for the critical configuration which indicates flutter at 600 knots. In Fig. 19, the *v-g* plot for the safe configuration is presented. At 600 knots, this configuration has about 4% *g* structural damping.

A clear picture of the existing nonlinearities is shown in Fig. 20, which presents the frequencies of the roll and the bending mode for small and large amplitudes. There is a large frequency difference, which effects the tuning of the system and thus also leads to amplitude limited flutter for distinct amplitudes. This frequency spread was reduced later in the program by increasing the preload of the wing-pylon attachment in roll.

Time histories of a store accelerometer on the store tip are presented in Fig. 21. This shows amplitude limited flutter at 610 knots excited by air turbulence.

Open Loop Tests

Open loop test results are shown in Fig. 22 for different sensor locations at approximately the same airspeed. Combination I cannot be used because the outer wing bending mode at 11.3 Hz becomes unstable encircling the point (+1) in the Nyquist diagram from the right side. Combination III is most suitable. A counter-clockwise phase shift is necessary for the pitch mode (5.5 Hz) to be optimally suppressed. This phase shift arises from the actuator transfer function, which has more phase lag than the one which was used in the calculation to find the control law. Such open loop tests must be performed because our system, with a complete state vector feedback, only takes into account two modes (store pitch and first wing bending), and all other modes must be excluded by bandpass filtering or filtering by location.

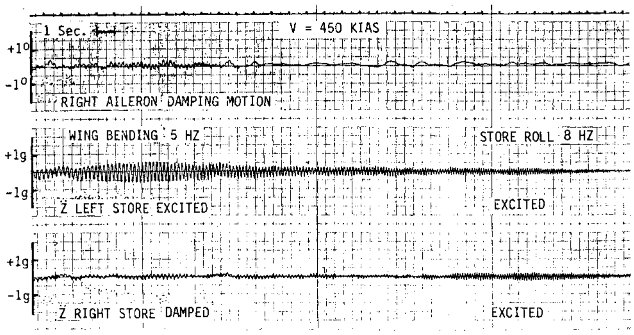

Fig. 23 Elastic mode damping at subcritical speeds.

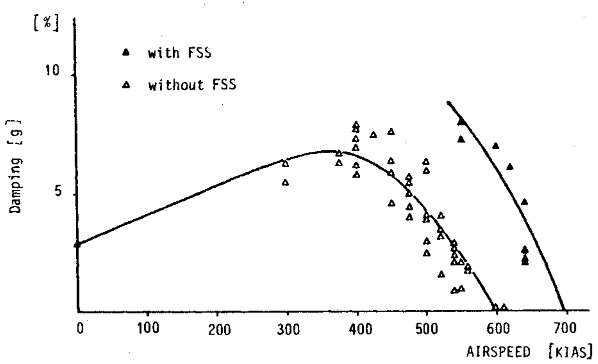

Fig. 24 Increase of flutter speed with FSS.

Closed Loop Tests

Closed loop tests were performed at subcritical speeds to demonstrate elastic mode suppression. This is shown in Fig. 23, where the right system was exciting and the left system was damping. Vibration amplitudes at 5 Hz are reduced considerably on the left wing, whereas the higher mode at 8 Hz remains unchanged because the FSS is uneffective at these frequencies. Flutter flights at high speeds were also undertaken. No divergent oscillations occurred, but it was proven that the FSS is working well (Fig. 24).

Acknowledgments

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