Active Flutter Suppression—An Emerging Technology

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Controlling aircraft elastic modes has been seriously considered during the past decade. Flight demonstration of Stability Augmentation Systems on the B-52 and XB-70 aircraft have demonstrated the value of suppressing stable structural modes. These programs and others which provide the basis to proceed with confidence to active control of unstable modes are discussed. The paper also covers the limited analytical studies accomplished on unstable or flutter modes.

Introduction

In recent years airframe design trends have shown a steady increase in flexibility, slenderness ratio, and maximum operating speeds, resulting in an increased likelihood of flutter within the aircraft operating envelope. Contemporary airframe designs are based primarily on strength requirements. This approach results in a configuration that meets strength criteria but the design may have insufficient stiffness to meet flutter requirements. Aircraft exhibiting this characteristic include the B-52, SST and B-1. Preliminary design trades recently performed by Boeing indicate that weight penalties as much as 2 to 4% of total structural weight may be required to solve potential flutter problems. Such weight penalties are significant in modern applications, where payload weight may be as small as 20% of structural weight.

The flutter problem is further compounded on tactical aircraft with external stores, particularly when the large combination and mixes of stores are considered. Additional flutter problems may be encountered with variable geometry designs which induce aerodynamic coupling between the empennage and wing.

Presently, flutter problems are solved by modifying the structure, adding mass balance, and establishing suitable flutter placards. These approaches are time consuming, involve weight penalties, and sometimes limit weapon system missions.

Within the last ten years control systems that suppress lower frequency structural modes have evolved from analytical feasibility studies to production hardware. Such a system is currently being installed on the B-52G and H fleet. To date, approximately 65% of the kits have been installed and the remaining kits will be installed by September 1971.

As a result of this new technological base, a flutter suppression system is now feasible, offering the potential, in many instances, for solving flutter problems with significantly less weight and performance penalties. These advantages cannot be ignored in an industry where weight and performance advantages are of prime concern.

This paper summarizes results of past modal suppression activities and discusses results of current studies in active flutter suppression—an emerging technology.

Past Modal Suppression Activities

Requirements to fly higher, faster and farther, have resulted in larger, more flexible airframes. This trend has made it more difficult to design aircraft having acceptable performance, stability and handling qualities throughout the mission profile. Large, high-speed, flexible aircraft normally have inadequate short period and Dutch roll damping, resulting in objectionable handling qualities. In addition, elastic modes of such aircraft are normally strongly coupled throughout the frequency spectrum, resulting in increased response to longer gust wave lengths and higher dynamic structural loading.

Automatic pilots have been used to control aircraft dynamics for over fifty years, although systems to control aircraft elastic modes have been considered seriously only during the past decade.[1-29] One of the earliest studies in active structural mode control is discussed in Ref. 1. This study discusses active control of a B-52 lateral body bending mode to reduce aft body structural fatigue damage rate. A lateral body damper system was synthesized to control a 1.25 Hz antisymmetric mode using the rudder with an aft body accelerometer for feedback. Figure 1 shows the system block diagram. Body bending responses with and without the system are compared in Fig. 2.

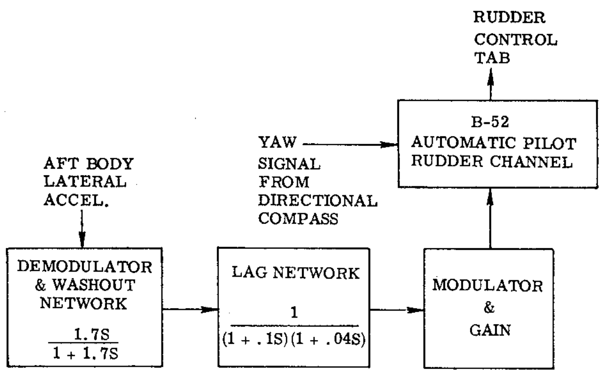

Fig. 1 Sperry B-52 lateral body damper block diagram.

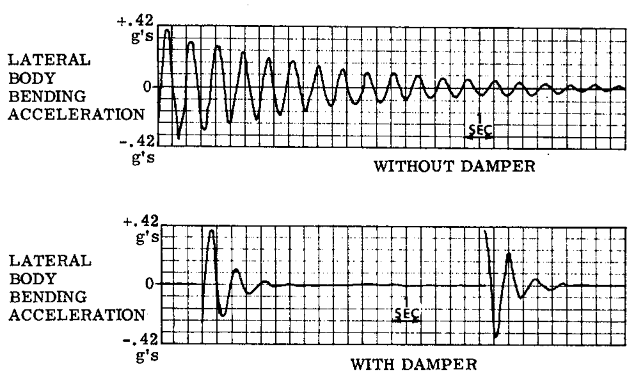

Fig. 2 Effect of Sperry B-52 lateral body damper.

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The B-52 was initially designed as a high-altitude bomber, but mission requirements were later expanded to include low-altitude, high-speed flight. Increased turbulence of the low-altitude environment results in larger peak loads, increased fatigue damage rate and reduced controllability. Severity of the low-level environment was vividly illustrated in 1964 by a low-level flight test incident near the Colorado Rocky Mountains in which a severe turbulence encounter exceeded the B-52 vertical tail design strength, severing the vertical tail.

This incident and recommendations from an Aeronautical Systems Division Special Committee on Aeronautical Design Practices and Criteria emphasized the need for an advanced flight control system on the B-52. The ECP 1195 Stability Augmentation System (SAS) was developed for the B-52G and H fleet to meet this need.[7–17] The ECP 1195 system was designed to reduce peak loading, reduce fatigue damage rate and improve controllability. Airplane angular rate and linear acceleration information are sensed, processed and fed to wide bandpass hydraulic actuators which drive the rudder and elevator control surfaces.

Damping of various structural modes with the SAS ON and OFF was determined during flight tests by exciting the structural modes with control surface sinusoidal motions. Control surface motions were controlled by an oscillator that could be varied in frequency, amplitude and number of cycles. The command to the surface actuator was manually tuned to excite only the selected structural mode. After a predetermined number of cycles, the commanded oscillation was stopped at exactly zero to prevent exciting structural modes other than the one being tested. Figure 3 shows a typical time history trace of a 1.4 Hz aft body bending mode excited by the rudder. The middle trace shows the unaugmented airplane in which the mode was allowed to decay after the two cycle excitation. The bottom trace shows damping of the mode with the SAS engaged. In this case, the SAS was engaged shortly after the rudder command was clamped to zero. Damping ratio of this structural mode at this flight condition exceeds 0.40 with the SAS. Figure 4 shows the improvement in after body lateral bending mode damping ratio as a function of dynamic pressure with the system engaged.

Typical flight test results showing after body side displacement in random turbulence with and without the SAS are shown in Fig. 5. With the SAS OFF the 1.4 Hz body bending mode dominates the response. The SAS reduces lateral RMS displacements by a factor of at least six.

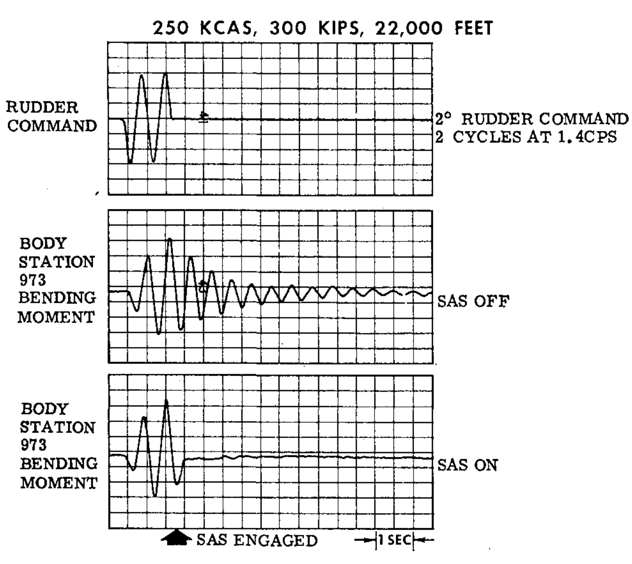

Fig. 3 Effect of ECP 1195 SAS on aft body bending.

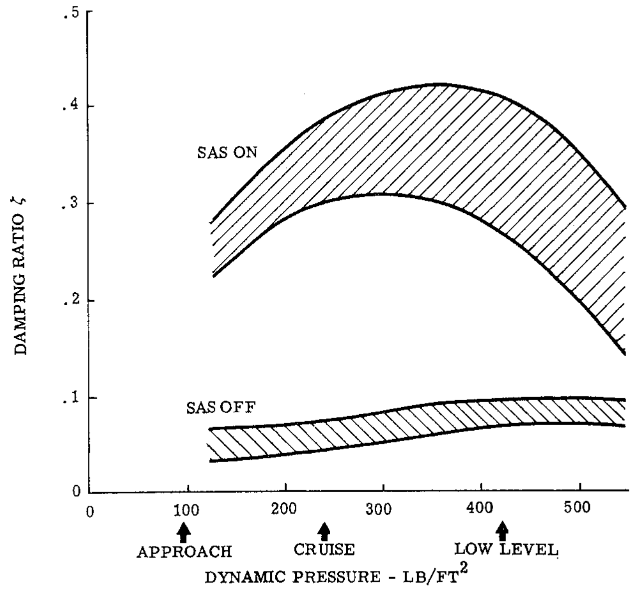

Fig. 4 Aft body lateral bending mode damping with ECP 1195 SAS.

Figure 6 summarizes B-52G and H fatigue damage rate with and without the ECP 1195 system. Fatigue damage rate is significantly reduced, particularly in the aft fuselage areas.

Mission flexibility was significantly improved with the ECP 1195 system in terms of fatigue damage rate and probable occurrence of overload. The upper portion of Table 1 compares the time for a B-52G or H airplane to accumulate a unit of fatigue damage operating at low level with and without the system. For equal fatigue damage the airplane with the SAS can: fly 11 times longer at 325 knots, fly 8.4 times longer at 400 knots, and fly 2.7 times longer at 400 knots than without the SAS at 325 knots.

The lower portion of the table compares relative time to reach an overload occurrence operating at the same conditions. For equal time to probable overload a B-52G or H airplane with the SAS can: fly 1000 times longer at 325 knots, fly 100 times longer at 400 knots, and fly 26 times longer at 400 knots than without the SAS at 325 knots.

Two structural mode control research programs were conducted under AFFDL direction concurrently with the

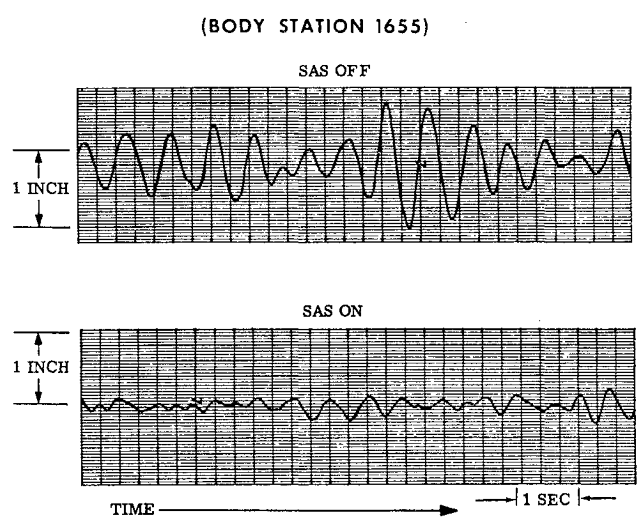

Fig. 5 Aft body side displacement in random turbulence with ECP 1195 SAS.

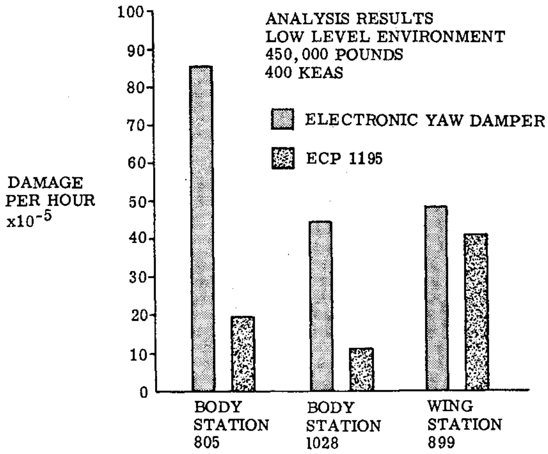

Fig. 6 B-52 fatigue damage rate reduction with ECP 1195.

Table 1 Mission flexibility with ECP 1195 SAS. B-52G and H fleet 350,000 lb gross weight low level environment

	Speed	Without SAS	With SAS
Time to equal fatigue damage	325 Keas	1	11
	400 Keas	0.32	2.7
Time to equal occurrence of overload	325 Keas	1	1000
	400 Keas	0.26	26

ECP 1195 program. Boeing and Honeywell jointly conducted a program "Load Alleviation and Mode Stabilization (LAMS),"[18–21] and North American Rockwell conducted an XB-70 program, "Gust Alleviation and Structural Dynamic Stability Augmentation System (GASDSAS)."[22–28]

The LAMS program was initiated in 1966 to demonstrate the capability of an advanced flight control system to alleviate gust loads and control wing structural modes on a large subsonic flexible aircraft using conventional aerodynamic control surfaces. The B-52 was selected for the test vehicle because its dynamic characteristics are representative of future generation large flexible aircraft and extensive airplane loads data are available. The specific goal of this program was to flight demonstrate a measurable reduction in wing fatigue damage rate caused by turbulence while retaining or improving aircraft handling qualities.

The LAMS program was designed to use existing ailerons, spoilers, elevators and rudder control surfaces as force producers. The airplane flight control system was modified to incorporate wide bandpass electrohydraulic actuators on the elevators, ailerons and rudder. The LAMS system was synthesized and demonstrated at three typical flight conditions. For comparison, a baseline SAS representing a contemporary stability augmentation system was designed to control only rigid body motions.

Fatigue damage rate improvements with the LAMS flight control system are shown in Fig. 7, based on an annual usage rate of 25 hr at a low-level, high-speed condition, 39 hr at a low-level, low-speed condition, and 511 hr at high-altitude cruise. Fatigue damage rates are compared with controls locked (no SAS), with the baseline SAS (rigid body control only), and with the LAMS flight control system. The LAMS system reduced wing fatigue damage rate approximately 50%.

The XB-70 GASDSAS program extended active control of aeroelastic modes to include supersonic flight. The objective of this program was to design a control system to reduce rigid body and structural mode accelerations of a low load factor flexible aircraft, flying at high speeds in a turbulent environment.

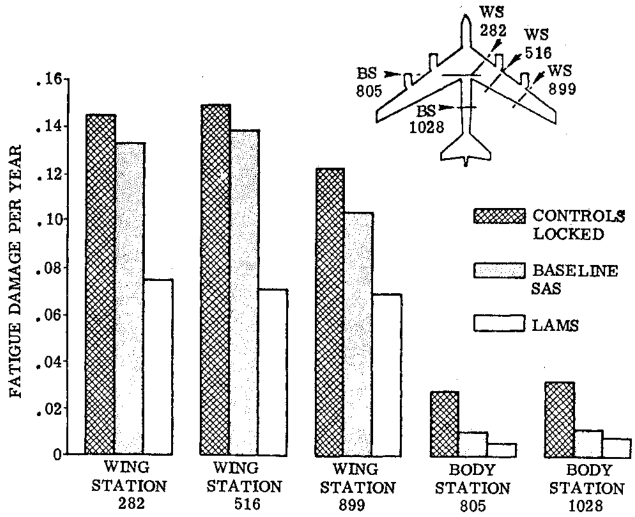

Fig. 7 B-52 fatigue damage rate reduction with LAMS (fatigue due to turbulence).

Two sensing schemes were investigated. One scheme employed Identical Location of Accelerometer and Force (ILAF) techniques using linear accelerometer blended signals. A second approach used blended signals from two remotely located angular accelerometers, known as the Differential Angular Acceleration (DAA) system. Both systems used the elevator, flap, aileron and rudder for force producers. In addition, small horizontal and vertical canards were shown to be effective for structural bending control. The ILAF system showed significant reductions in fuselage vertical accelerations, as indicated in Fig. 8.

Analytical and simulation studies were initiated by Boeing in 1967 to determine potential benefits of active mode control on Supersonic Transport variable sweep and fixed wing configurations. SAS configurations were evaluated for performance improvements in three areas; ride smoothing, controllability and flutter.

The ride smoothing analysis indicated that the first four body modes in the vertical plane, covering a frequency range from approximately 1.4 to 3.8 Hz, contribute significantly to gust induced accelerations. The ride smoothing SAS concept was designed to suppress these elastic vibration modes without significantly affecting rigid body dynamics. Figure 9 illustrates fuselage vertical accelerations for a typical subsonic descent condition with and without a ride smoothing SAS. The upper curves are total vertical accelerations, the lower curves are rigid body contributions, and the differences between the curves are aircraft flexible mode contributions.

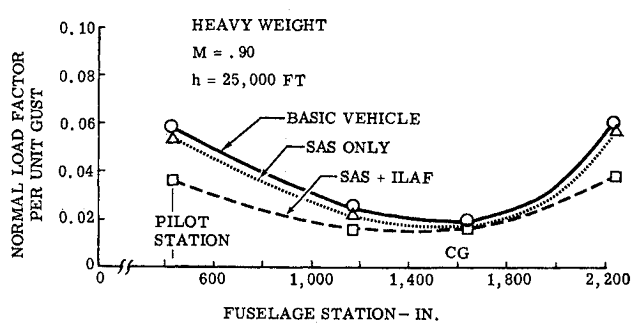

Fig. 8 XB-70 acceleration reduction with ILAF system.

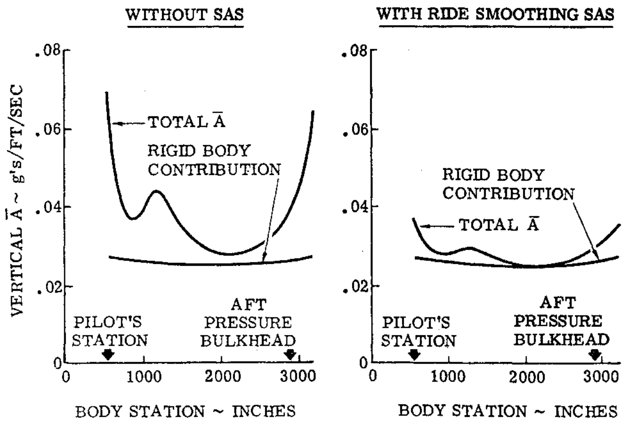

Fig. 9 SST vertical accelerations with and without ride smoothing SAS (subsonic descent condition).

The ride smoothing SAS significantly reduces vertical accelerations at the forward and aft ends of the aircraft, where accelerations are largest.

Honeywell also conducted SST ride smoothing mode control analyses, showing a 50% reduction in RMS acceleration at extreme forward and after stations.[29]

Boeing and North American have conducted mode control analyses for the B-1, showing significant improvements in ride qualities and fatigue damage rate. North American plans to incorporate a mode suppression ride smoothing system on the B-1, as discussed in Ref. 30.

In the past, wind-tunnel testing of dynamically scaled airplane models has proven economically desirable to predict airplane dynamic characteristics prior to flight testing. As aircraft become more dependent on stability augmentation systems, wind-tunnel testing of aeroelastic models to prove control concepts will become increasingly more attractive for reducing flight testing, as discussed in Ref. 31. Consequently, in 1967, AFFDL and NASA-Langley jointly initiated a program to demonstrate an active modal suppression system on a one-thirtieth scale B-52E aeroelastic model in the Langley transonic dynamics tunnel. This model will include aileron and elevator actuation systems and provisions for a cable mount system.[32] Model gust responses have been obtained using the airstream oscillator system installed in the tunnel.[33] Boeing-Wichita is assisting NASA in developing a ride smoothing system for the model using 50 Hz bandwidth aileron and elevator actuation systems. Initially, the model will be used to determine airplane stability derivatives for comparison with flight test data. Subsequently, canards and flaperons will be added for ride smoothing wind-tunnel testing.

Past Flutter Suppression Studies

The studies and flight demonstrations discussed previously have provided the technolgical base and confidence to proceed into active flutter suppression. As modal suppression analytical techniques were developed, it became increasingly apparent that these same techniques, with relatively minor modifications, could be applied to active flutter suppression system syntheses.

In 1968, Boeing-Wichita began studies to determine the feasibility of actively damping two flutter modes on a delta wing SST strength designed configuration.[34] At Mach 0.90 the configuration has a 3.5 Hz wing mode and a 2.8 Hz body-wing mode with zero damping at speeds less than 1.2 V_{Dive} (V_D) requiring over 10,000 lb of additional structure to provide an adequate flutter margin. Studies were conducted to determine the feasibility of damping these modes with a flutter suppression system (FSS) to eliminate this additional weight.

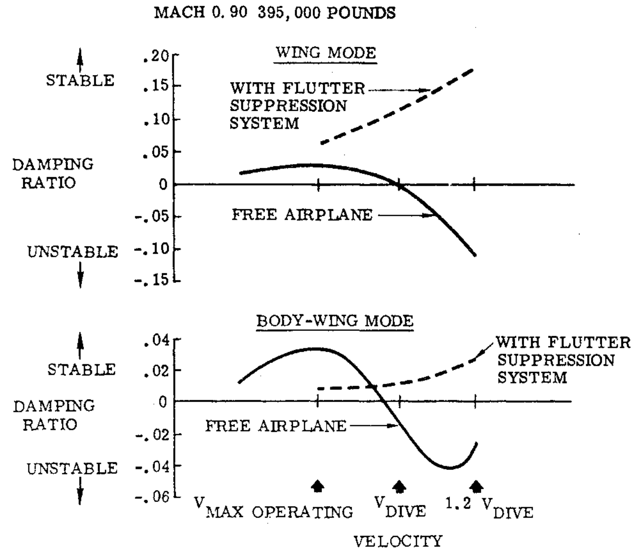

Fig. 10 Effects of active flutter suppression on SST.

Figure 10 shows damping ratios of the two flutter modes, with and without the FSS. The system uses wing tip aileron surfaces and two wing mounted pitch rate gyros. Without the FSS the airplane becomes unstable at 0.96 V_D. The FSS extends flutter beyond 1.2 V_D. A root locus of the two SST flutter modes as a function of velocity is shown in Fig. 11.

During the same time period analyses and wind-tunnel tests were conducted by Lockheed-Georgia to demonstrate servo-control of aeroelastic structures for delaying flutter onset.[35] The study included analog simulation and wind-tunnel tests to confirm that the flutter speed could be increased 20% with the control system.

Under the direction of A. Gerald Rainey, the Aeroelasticity Branch of NASA-Langley has also conducted active flutter suppression analyses. Dr. Eliahu Nissim developed a FSS concept for a large supersonic transport wing configuration.[36] The wing will be tested in the NASA-Langley transonic dynamics wind tunnel to demonstrate the concept. Boeing-Wichita has been working with NASA in synthesizing a system for the wing, based on the Nissim concept.[37] Figure 12 shows flutter speed improvement for a FSS employing leading and trailing edge surfaces. NASA plans to conduct

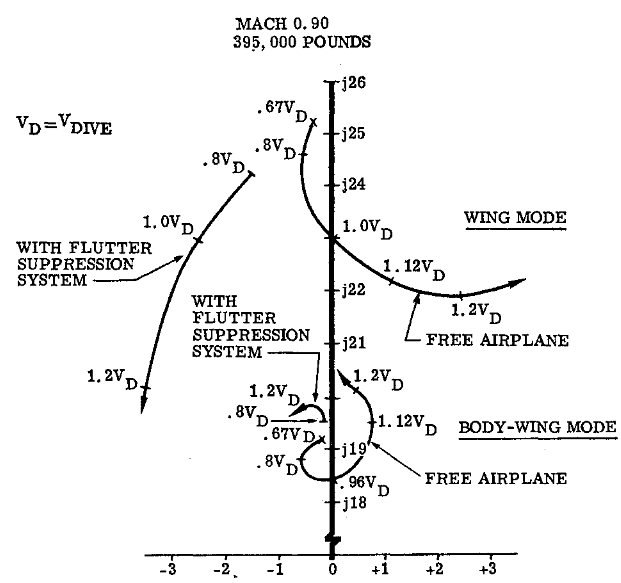

Fig. 11 SST root locus with active flutter suppression system.

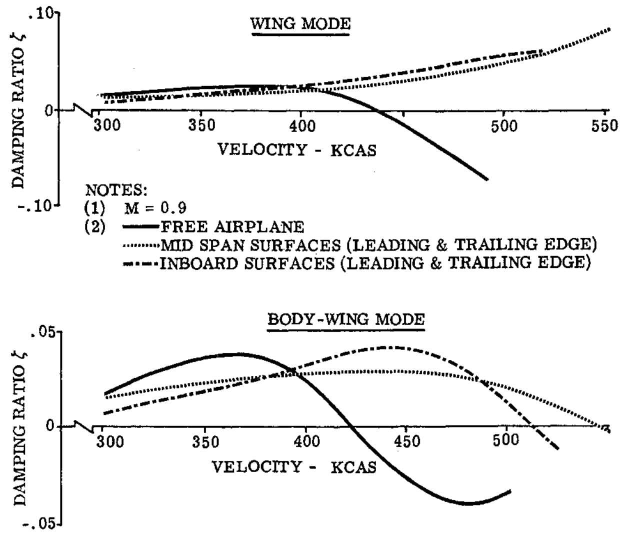

Fig. 12 Nissim flutter suppression system performance.

model wind-tunnel tests to determine leading and trailing edge control surface hinge moments and then to mechanize the FSS on the model.

Under an AFFDL contract, Boeing-Wichita recently completed an anlytical study to determine the feasibility of demonstrating a flutter system on the B-52E LAMS test airplane.[38] A flutter condition was analytically produced at approximately 335 KIAS at 21,000 ft using adverse fuel distribution with 2,000 lb of ballast in the extreme forward end of the 3000 gallon external tanks. This configuration results in a 2.4 Hz symmetric wing bending and torsion flutter mode. Existing inboard ailerons, new middle span ailerons, new outboard (tip) ailerons, and the existing elevator were considered for flutter control. The existing inboard aileron is the best single control surface for controlling the flutter mode, as shown in Fig. 13. Figure 14 illustrates the inboard aileron flutter suppression system block diagram. With adverse gain, phase and sensor variation tolerances, this system increases the flutter placard airspeed 37%, as shown in Fig. 15.

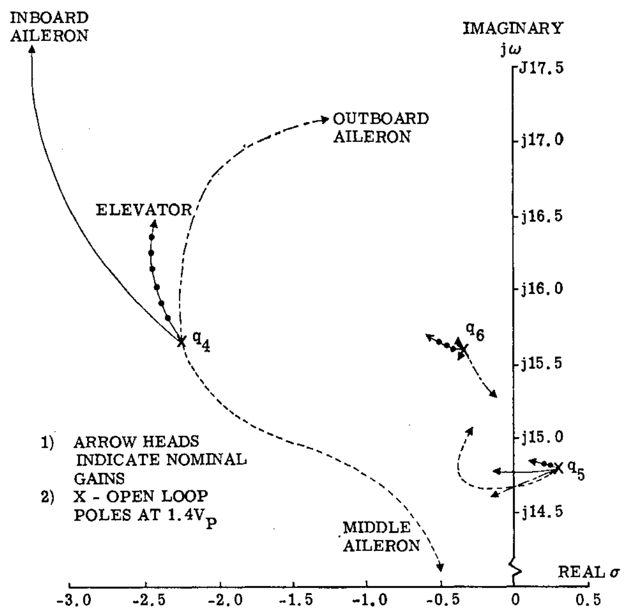

Fig. 13 Root locus comparison of potential flutter suppression control surfaces.

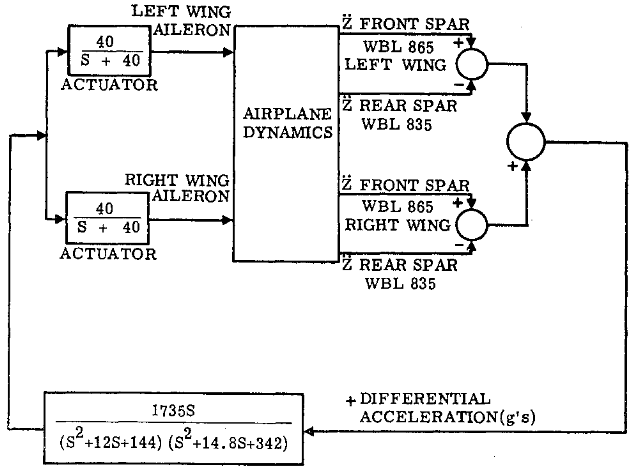

Fig. 14 Inboard aileron system block diagram.

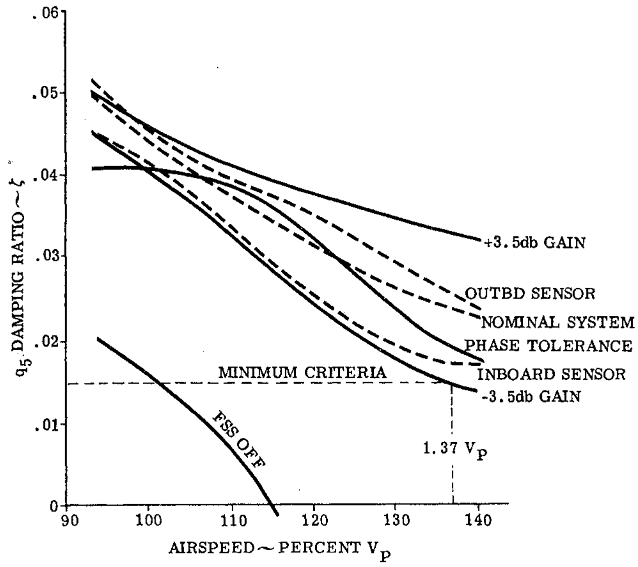

Fig. 15 Effect of variations on inboard aileron system performance.

A multiple control surface configuration, consisting of existing inboard aileron and a new middle aileron was also investigated. This system increases the flutter placard airspeed over 40%, with adverse tolerances included.

Conclusions

Analytical studies indicate that active flutter suppression is technically feasible and offers significant weight savings. Programs such as ECP 1195, LAMS and ILAF have demonstrated the value of suppressing stable structural modes. Active control of unstable modes, defined as flutter, is the next logical step. A coordinated active flutter suppression research program is needed to investigate applications, payoffs, criteria, synthesis techniques and to demonstrate performance. Flight demonstrations are particularly important for industry and government acceptance. As aircraft continue to increase in speed, size and aerodynamic efficiency, flutter problems will become more critical and solutions will become more costly. Active flutter suppression is emerging as a technology offering practical, cost-effective solutions to such problems.

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