ACTIVE VERTICAL TAIL BUFFETING ALLEVIATION ON AN F/A-18 MODEL IN A WIND TUNNEL

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ABSTRACT

A 1/6-scale F-18 wind-tunnel model was tested in the Transonic Dynamics Tunnel at the NASA Langley Research Center as part of the Actively Controlled Response Of Buffet-Affected Tails (ACROBAT) program to assess the use of active controls in reducing vertical tail buffeting. The starboard vertical tail was equipped with an active rudder and other aerodynamic devices, and the port vertical tail was equipped with piezoelectric actuators. The tunnel conditions were atmospheric air at a dynamic pressure of 14 psf. By using single-input-single-output control laws at gains well below the physical limits of the control effectors, the power spectral density of the root strains at the frequency of the first bending mode of the vertical tail was reduced by as much as 60 percent up to angles of attack of 37 degrees. Root mean square (RMS) values of root strain were reduced by as much as 19 percent. Stability margins indicate that a constant gain setting in the control law may be used throughout the range of angle of attack tested.

1. INTRODUCTION

Buffeting is an aeroelastic phenomenon which plagues high performance aircraft especially those with twin vertical tails. As shown in figure 1, for aircraft of this type at high angles of attack, vortices emanating from wing/fuselage leading edge extensions (LEX) burst, immersing the vertical tails in their wake. The resulting buffet loads on the vertical tails are a concern from fatigue and inspection points of view [1-4]. For example, for the McDonnell-Douglas F/A-18, special and costly 200-flight-hour inspections are required to check for structural damage due to buffet loads [4]. Inspections and repairs are high cost items to the military services.

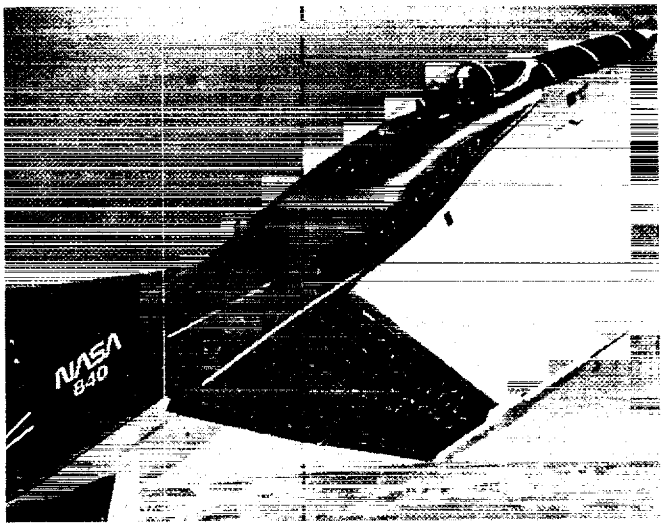


Figure 1. Flow Visualization of Leading Edge Extension (LEX) Vortex Burst, 30 degrees AOA

To reduce fatigue and thus increase the life of a vertical tail, the stresses caused by buffeting must be reduced. This reduction may be accomplished by 1) modifying the load-carrying structure within the tail, 2) reducing the buffet loads by altering the flowfield around the vertical tail, or 3) by reducing the buffeting response through active control of effectors on the tail. The success of a proposed fix to the buffeting problem has generally been measured by percentage reduction in the root mean square (RMS) of the strain at the root of the vertical tail.

For the purpose of understanding the buffeting problem, several programs have focused on quantifying the buffet loads by acquiring response measurements and surface pressures on the vertical tails of scaled models in a wind-tunnel and on an actual aircraft during flight[1-3, 5, 6]. In general, the results of these studies are published as spectra and pressure coefficients for the inboard and outboard surface of the tail.

Based on some of these studies, McDonnell-Douglas Aircraft (MDA) implemented an interim solution on the F-18 relying entirely upon structural modifications to the vertical tail in an attempt to reduce the dynamic stresses in critical areas[2]. Even with the structural enhancement, the dynamic stresses were still too severe. This led to the investigation of a LEX fence which reduced the peak accelerations in the first two modes of the vertical tail but also compromised the aircraft's high-alpha performance by reducing the unsteady lift and pitching moment of the aircraft[2]. Therefore, other options needed to be explored.
In 1992, the concept of an actively controlled rudder was proposed to alleviate vertical tail buffeting on an F-18 and an F-15 aircraft[7]. This analysis showed that an actively controlled rudder of an F-18 might be effective in adding damping to the vertical tail resulting in reductions in the RMS of the root bending moment.

In 1995, the use of actively controlled piezoelectric actuators on an F/A-18 vertical tail was analyzed[8]. This analysis showed that actively controlled piezoelectric actuators might increase damping greater than 60% in the first bending mode for less than an 8% increase in the weight of the vertical tail.

In 1995, vertical tail buffeting alleviation was achieved using piezoelectric actuators on a 5%-scale 76-/40-deg double delta wing wind-tunnel model with twin vertical tails that were not canted[9]. Over ranges of angle of attack from 20 to 55 degrees and dynamic pressure from 0.5 to 7 psf, peak response of the vertical tail was reduced by as much as 65% over the uncontolled response, using simple control algorithms employing collocated strain gauges.

In 1995, a wind-tunnel investigation at the Transonic Dynamics Tunnel (TDT) at the NASA Langley Research Center (LaRC) demonstrated that buffeting alleviation of the vertical tails on an F-18 can be achieved using active piezoelectric actuators or rudder [10]. The research objectives of the Actively Controlled Response Of Buffet-Affected Tails (ACROBAT) program are twofold: 1) to determine the spatial relationships of the differential pressures during open-loop and closed-loop conditions at various angles of attack; and, 2) to apply active controls technology, using a variety of force producers, to perform buffeting alleviation on twin vertical tails of a 1/6-scale F-18 wind-tunnel model. This investigation is the first experimental demonstration of active buffeting alleviation on a scaled F-18 wind-tunnel model using an active rudder and piezoelectric actuators.

The purpose of this paper is to present some open-loop and closed-loop wind-tunnel results using an active rudder or piezoelectric actuators to alleviate vertical tail buffeting. The results of the wind-tunnel tests presented herein demonstrate the feasibility of actively controlling vertical tail buffeting.

2. WIND-TUNNEL MODEL

An existing 1/6-scale, rigid, full-span model of the F/A-18 A/B aircraft was refurbished, and three flexible and two rigid vertical tails were fabricated. This model was then sting-mounted in the Transonic Dynamics Tunnel (TDT) at the NASA Langley Research Center, as shown in figure 2, where it underwent a series of tests to determine buffet flowfield characteristics and to demonstrate the alleviation of vertical tail buffeting.

Figure 2. 1/6-Scale F/A-18 Model Mounted in the Transonic Dynamics Tunnel

Figure 3: Side View of 1/6-Scale F/A-18 Model Mounted in the TDT

The three flexible tails were fabricated from a 1/8-inch thick aluminum plate and covered with balsa wood. The aluminum plate thickness was chosen such that the frequencies of the first three modes were close to those of the full-scale tail. Also, by using a frequency scaling near unity, the effects of actuator bandwidth could be compared directly between full-scale and reduced-scale results. All three flexible tails were instrumented with a root strain gauge aligned to measure bending moment and with two tip accelerometers near the leading and trailing edges. The two rigid tails (one port, one starboard) were fabricated from a block of aluminum and were geometrically identical to the flexible tails.

Figure 4. Piezoelectric Actuator Arrangement on Port Flexible Tail, Hatch Cover Removed

To investigate active buffeting alleviation, the flexible tails included the following control effectors: 1) a rudder surface; 2) a tip vane configuration containing a slotted cylinder; 3) piezoelectric actuation devices; or 4) an embedded slotted cylinder. The rudder, the tip vane, (shown in figure 3), and the embedded slotted cylinder were activated by clamping each of them (when necessary) to a drive shaft that was turned by a hydraulic actuator located below the root of the vertical tail. Each of the seven piezoelectric actuators consisted of two individual actuators that were commanded to strain in opposite directions simultaneously. By commanding the (pair of) actuators in this fashion, the tail could be bent. The piezoelectric actuators, whose individual actuators located on the inboard surface are shown in figure 4, were powered by individual amplifiers located outside the test section of the TDT. Not counting bonding material, each individual piezoelectric actuator at the root of the vertical tail consisted of two stacks of four layers of encapsulated wafers. The individual actuators at other span locations consisted of two stacks of two layers of encapsulated wafers. Each individual actuator at the root had dimensions of 4.00"x1.50"x0.06" and weighed 1.02 ounces (2.1% of total vertical tail weight). Each individual actuator at other span locations had dimensions of 4.00"x1.50"x0.03" and weighed 0.51 ounces. There are a total of six individual actuators at the root and eight individual actuators elsewhere. For the port flexible tail with active piezoelectric actuators, the first bending mode is around 14 Hz (wind-off) and the first torsion mode is around 62 Hz (wind-off).

3. TEST CONDITIONS

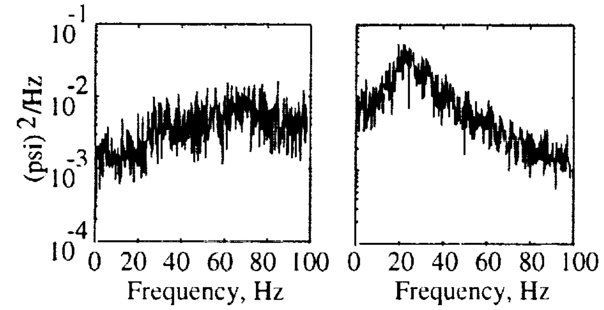
For buffet, the Strouhal number is the primary scaling relationship used in determining tunnel conditions[1]. The Strouhal number, *n*, is a nondimensional frequency parameter that is proportional to reduced frequency, and is expressed as

$$n = \frac{f \cdot c}{U} \qquad (1)$$

where f is frequency in Hz, c is characteristic length, and U is velocity. Since active controls were a primary focus, comparisons of actuator bandwidths between model and flight were an issue. Therefore, to avoid any difficulties in scaling and defending any possible discrepancies, unity was chosen as the frequency ratio between model and aircraft structural modes and forcing function spectra.

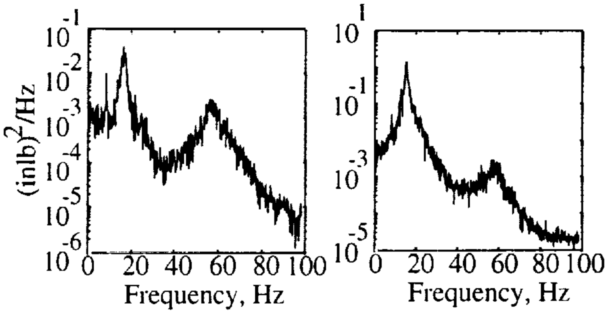
4. GENERAL BUFFET AND BUFFETING CHARACTERISTICS OF THE WIND-TUNNEL MODEL

Typically, the buffet and buffeting are quantified by their dimensional or nondimensional power spectral density (PSD) functions. Since the results reported for this test are not being compared to other model or aircraft data, the dimensional form is used. For the1/6-scale F-18 model, the plots of the unsteady differential pressures of the buffet at angles of attack of 20 and 34 degrees are shown in figure 5. The differential pressures were computed from the pressure time histories acquired near the center of the planform of the starboard flexible tail. The buffet at 20 degrees AOA, in figure 5(a), appears broad band compared to the buffet at 34 degrees AOA, in figure 5(b). At 34 degrees AOA, an aerodynamic resonance around 25 Hz has emerged with a magnitude that is at least one order of magnitude larger than the levels at 20 degrees AOA. These trends of the pressures with angle of attack are consistent with other experimental data[1, 3].



(a) 20 Degrees AOA (b) 34 Degrees AOA

Figure 5. PSDs of Differential Buffet Pressure, Midspan Midchord, Starboard Flexible Tail, 14 psf



(a) 20 Degrees AOA (b) 34 Degrees AOA

Figure 6. PSDs of Root Bending Moment Buffeting Response, Starboard Flexible, 14 psf

The pressures, shown in figure 5 (a)-(b), created the buffeting, or structural response to the buffet, shown in figure 6 (a)-(b), respectively. At 34 degrees angle of attack, the buffeting shown in figure 6(b) around 14 Hz, which corresponds to the first bending mode of the vertical tail, has intensified by 1.5 orders of magnitude above the level at 20 degrees AOA, shown in figure 6(a). Since the buffet, or force input to the tail, around 25 Hz has grown with increased angle of attack, as indicated by figure 5, the vertical tail buffeting in the first bending mode has also grown with increased angle of attack, as indicated by comparing figures 6 (a) and 6 (b). The response in the mode around 58 Hz has not grown significantly with the increase in angle of attack because the magnitudes of the pressures in that portion of the spectrum have not increased with increased angle of attack, as seen in figure 5. Referred to as "open-loop" buffeting, the structural responses due to the buffet only (without a commanded signal to the rudder or piezoelectric actuators) peaked at an angle of attack of approximately 34 degrees for the 1/6-scale F-18 model. This peak at 34 degrees angle of attack agrees well with the results of other wind-tunnel tests[1, 3].

Another influence of the buffet on the vertical tail buffeting was seen by comparing the first bending frequency of the vertical tail as angle of attack was changed. The frequency of the first bending mode shifts to a lower value as angle of attack is increased (figure 7). This gradual shift in frequency with angle of attack was seen in the results of the wind-tunnel test reported on in Reference 1. If the vertical tail is considered a single degree-of-freedom system subject to the large perturbations in the flow due to the burst vortex, then this shift in frequency may be viewed as the result of increased aerodynamic damping of the first bending mode. During the ground vibration test of the starboard flexible tail, the structural damping was computed as approximately 1.8 percent for the wind-off damped first bending mode. Using the relationship between damped frequency and natural undamped frequency, the undamped natural frequency of the tail was calculated and used in estimating the total damping from the damped natural frequencies observed in the wind-tunnel at each angle of attack. The aerodynamic damping was calculated simply by subtracting the wind-off damping from the total damping. As seen in table 1, the aerodynamic damping reaches approximately 7 percent at 37 degrees angle of attack. This trend of aerodynamic damping with angle of attack was observed when comparing the frequency separation between half-power points on the power spectral density plots of the root bending moment at several angles of attack.

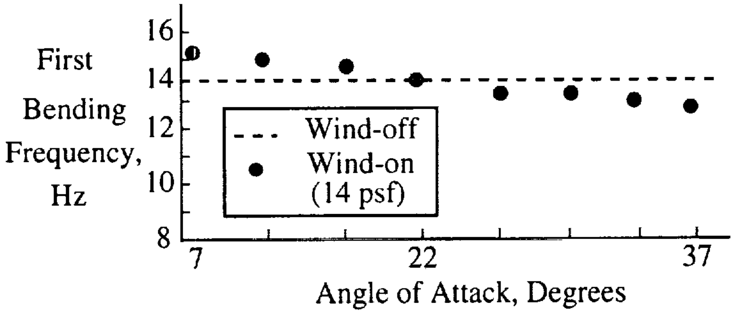


Figure 7. Variations of First Bending Frequency vs. Angle of Attack

Table 1. Estimates of Aerodynamic Damping Associated With Vertical Tail First Bending Mode

Angle of Attack, deg	Aerodynamic Damping, %
26	4.2
30	4.2
34	5.6
37	7.0

5. SYSTEM IDENTIFICATION OF THE WIND-TUNNEL MODEL IN PREPARATION FOR ACTIVE VERTICAL TAIL BUFFETING ALLEVIATION

The open-loop frequency response functions of the vertical tails due to the piezoelectric actuators were acquired experimentally by performing fast Fourier transforms[11] on the time histories of the responses of the commanded actuators and sensors located on the vertical tails. On-line capabilities at the TDT allowed quick computations of frequency response functions from time histories acquired just minutes earlier. No analytical predictions of the frequency response functions were made in advance of the wind-tunnel test because no analytical models of the aerodynamics associated with buffet were available at that time. The open-loop frequency response functions reported herein were obtained at a dynamic pressure of 14 psf in atmospheric air.

Several commands were sent separately to each actuator for determining the open-loop frequency response functions. To concentrate on the first bending mode around 15 Hz, a maximum frequency of 20 Hz was generally used in a linear frequency sweep. At times, linear sweeps up to 40 Hz were used to determine the influences of modes at frequencies higher than the frequency of the first bending mode of the vertical tail. In some cases, periodic pseudo noise (PPN) was used since this signal randomly selects the frequency content rather than sweeping through a mode which could result in damage to the wind-tunnel model. A matrix of transfer functions was obtained for all control effectors (as input) and the following outputs: strain at the root of the vertical tail, tip accelerations near the leading edge of the vertical tail, and tip accelerations near the trailing edge of the vertical tail.

The effectiveness of the seven piezoelectric actuator pairs were studied individually during tail buffeting. The three pairs of actuators at the root of the vertical tail were grouped together to boost actuator authority in the first bending mode. The remaining four pairs of actuators were abandoned because of their lack of authority in the higher tail modes. An open-loop frequency response function of the 3 pairs of piezoelectric actuators (grouped together as a single actuator) with respect to an accelerometer at the tip near the leading edge is shown in figure 8 for 24 degrees angle of attack. For comparison, an open-loop frequency response function of the rudder with respect to an accelerometer at the tip near the leading edge is shown in figure 9 for 26 degrees angle of attack. The hydraulic actuator resonance was around 24 Hz while the rudder-torque tube resonance was around 35 Hz, which contributed to the magnitude shown in figure 9.

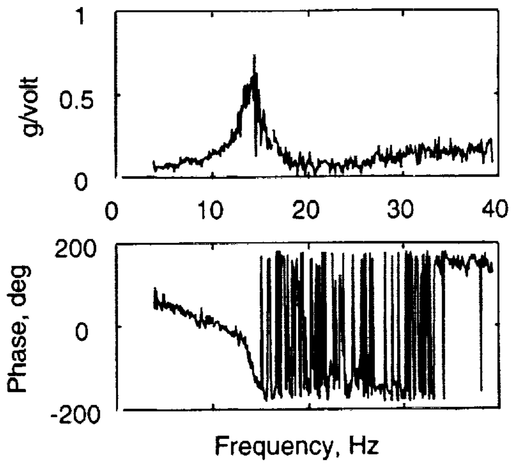


Figure 8. Open-Loop Frequency Response Functions Between Tip Acceleration and Piezo Actuator Command, 14 psf, 24 Deg AOA

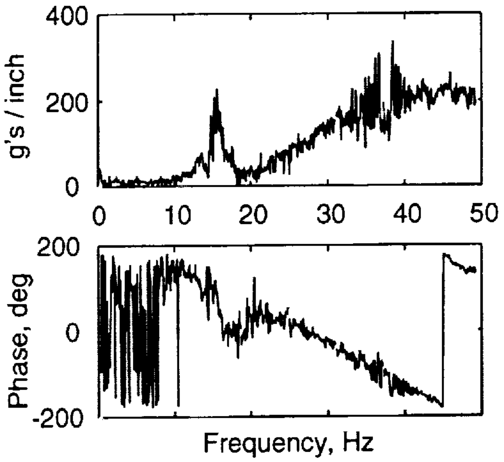


Figure 9. Open-Loop Frequency Response Functions Between Tip Acceleration and Rudder Command, 14 psf, 24 Deg AOA

Each open-loop frequency response function between actuator command and tip acceleration, shown in figures 8 and 9, is the input-output relationship of the forward loop of the active control system, shown in figure 10. As shown in figure 10, buffet contributes to the response (output) of the vertical tail (accelerations for this case). For the purpose of computing open-loop transfer functions, the response (output) time histories obtained when the tail was buffeting will contain contributions from the unmeasured buffet (input) and the measured actuator responses (input). Therefore, some uncertainty will exist in the open-loop frequency response functions computed from these time histories because of the unmeasured buffet.

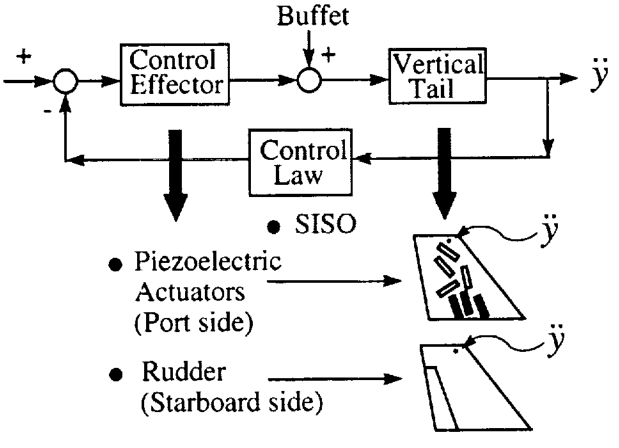


Figure 10. Active Control System

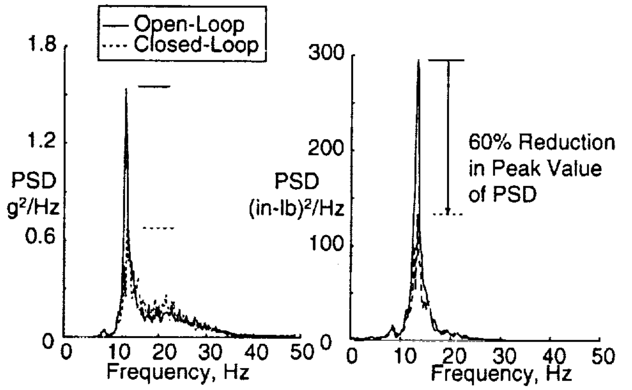
6. Control Law Design For The Buffeting Alleviation System

Using the open-loop frequency response functions obtained during the test, control laws were designed using frequency domain compensation methods[12]. These control laws were single-input, single-output control laws that utilized either a tip accelerometer or a root strain gage as the sensor to alleviate the response in the first bending mode. Because of some uncertainty in the measurement of the response created by the buffet, the control laws were designed based on the open-loop frequency response functions acquired at the lower angles of attack where the buffet, and the uncertainty in the plant, were much less. Since the buffeting of the vertical tail is maximum at 34 degrees, the feedback signal is maximum at 34 degrees. This maximum feedback signal was used in determining the constant gain setting of the control law.

The components of the active control system, shown in figure 10, include an analog-to-digital converter (A/D), a digital controller[13] in which the control law is implemented, and a digital-to-analog (D/A) converter. Since there were time delays associated with the digital controller and the actuator, the best approach to control law design was to take advantage of these phase lags. By lagging accelerations by ninety degrees of phase, the commanded motion of the actuator will provide damping to reduce the buffeting of the tail. For the rudder, the hydraulics and servo system were the major contributors to the phase lags. For the piezoelectric actuators, the digital controller was the major contributor to the phase lags. Because the frequency of the first bending mode was higher at the lower angles of attack, as shown in figure 7, the control law was designed to provide a total lag of 90 degrees at the frequency of the first bending mode expected at the higher angles of attack (see figure 7). In designing the control law, it was assumed that the phase relationship between tip accelerations and actuator command would not be a function of angle of attack. The resonance of the piezoelectric actuators was not encountered but was well above 100 Hz. Therefore, significant filtering was added to the control law to reduce its gain at frequencies above the first bending mode so that modes at higher frequencies were not affected. A notch filter around 35 Hz was used to prevent rudder motion near this frequency. Numerous levels of filtering in the control law were investigated analytically until arriving at the baseline control law for each actuator. The baseline control law design simply subtracted phase at the first bending mode so that the phase of the actuator lagged tip accelerations by ninety degrees at the frequency of the first bending mode.

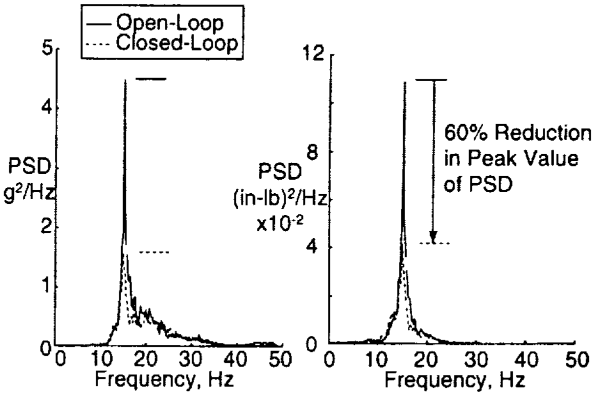
7. ACTIVE BUFFETING ALLEVIATION RESULTS

In figures 11(a) and 11(b), the open-loop and closed-loop tip accelerations and root strains (bending moment), respectively, at 34 degrees angle of attack are overlayed on the same plot to illustrate the buffeting alleviation created by actively controlling the piezoelectric actuators. Similar buffeting alleviation results were achieved using the rudder, as shown in figure 12. The peak value of the PSD of the root bending moment at the frequency of the first bending mode has been reduced by approximately 60% while the RMS value of the total signal was reduced by approximately 19%.



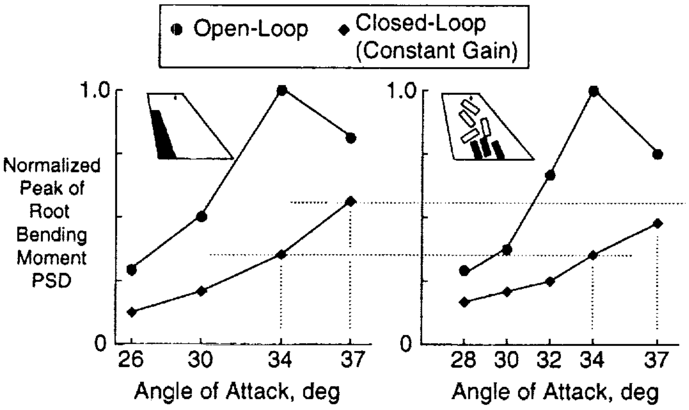
(a) Tip Acceleration (b) Root Bending Mom.

Figure 11. Comparison of Selected Responses for Open-Loop (Dotted Line) and Closed-Loop (Solid Line) Piezoelectric Actuators, 14 psf, 34 Degrees AOA



(a) Tip Acceleration (b) Root Bending Mom.

Figure 12. Comparison of Selected Responses for Open-Loop (Dotted Line) and Closed-Loop (Solid Line) Rudder, 14 psf, 34 Degrees AOA



(a) Rudder Results (b) Piezo Results

Figure 13. Comparisons of the Peak Values of the PSD of the Root Bending Moment at the Frequency of the First Bending Mode for Open-Loop and Closed-Loop Conditions, At Various Angles of Attack, 14psf

The actively controlled actuators provided damping to the tail for other angles of attack, as summarized in figure 13. The values reported in figure 13 are the (peak) value of the PSD curve of the root bending moment at the frequency of the first bending mode. Each value reported in figure 13 have been normalized to the maximum open-loop value which occurs at 34 degrees angle of attack. A constant gain setting was used for each actuator for all angles of attack values shown in figure 13. At 34 degrees angle of attack, 3 degrees (RMS) of the 20 degrees available and 2.4 volts (RMS) of the 10 volts available were used by the rudder and the piezoelectric actuators, respectively, to alleviate the vertical tail buffeting. The amount of buffeting alleviation obtained with the rudder is quite similar to that obtained with the piezoelectric actuators. At 34 degrees angle of attack, the open-loop value of the PSD for root bending moment has been reduced by approximately 60 percent using either control effector (see figures 11 and 12 also). Therefore, for the gain selected during the test, the alleviation performance of each control effector are approximately identical.

For each baseline control law, stability calculations[14] were performed at numerous angles of attack prior to closing the loop. In figure 14, the stability gain margins (GM) illustrate that the baseline control law for the rudder, and for the piezoelectric actuators, with a constant gain setting will not cause any instabilities. For the rudder, the gain margin decreases initially with increases in angle of attack up to 30 degrees. Gain margin increases with increases in angle of attack after reaching 30 degrees. For the piezoelectric actuators, the gain margin decreases with increases in angle of attack after reaching 24 degrees.

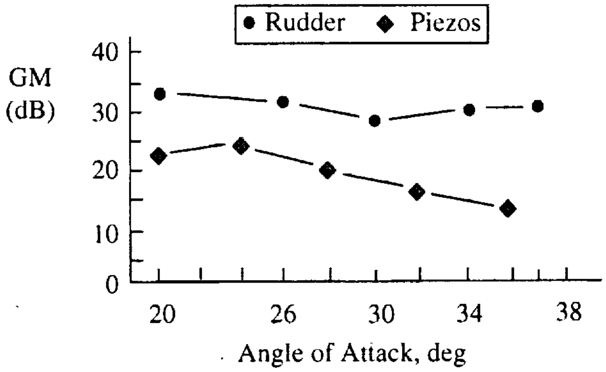


Figure 14. Gain Margins of the Baseline Control Laws For The Rudder and The Piezoelectric Actuators at Constant Gain, For Various Angles of Attack, 14 psf

Although the angle-of-attack trends of the gain margins vary between the two actuators, the gain margins remain greater than zero which indicates stability of the systems. Because the unmeasured buffet (input) is contributing to the magnitude of the frequency response function used in the stability calculations, the buffet may be the cause of the decrease in GM at the higher angles of attack. For the rudder at the higher angles of attack, a slight loss of force output will reduce the magnitude of the frequency response function slightly. This decrease in magnitude may be offsetting the increases from the buffet resulting in a relatively level gain margin curve, as shown in figure 14.

Setting the gain of the control law so that actuator performance was not exhausted at the worst case (34 degrees angle of attack) condition did not exclude the alleviation of buffeting at other angles of attack, as seen in figure 13. Based on the closed-loop and stability results in figures 13 and 14, respectively, it is anticipated that further improvement in the closed-loop response may be achieved by simply adjusting the gain in the control law to higher (still stable) values, thereby improving upon the percentage of total damping added to the system through the use of active controls.

8. CONCLUSIONS

During the wind-tunnel tests of the ACROBAT program's 1/6-scale F-18 model in the Transonic Dynamics Tunnel, reductions up to 60% in the peak value of the PSD of the root bending moment at the frequency of the first bending mode were observed when using actively controlled piezoelectric actuators or rudder at gains well below their physical limits. For the piezoelectric actuators, only 2.4 volts (RMS) were used of the 10 volts available to obtain the large reductions in root bending moment at 34 degrees angle of attack. At 34 degrees angle of attack, the rudder used only 3 degrees (RMS) of the 20 degrees available. For the gain settings tested in the wind-tunnel, the rudder and the piezoelectric actuators appeared equally effective in adding damping to the vertical tail during buffeting. The stability margins of the system indicated that the gain of the control law may be increased without driving the first bending mode of the vertical tail unstable. Despite the changes in the structural dynamics of the vertical tail with angle of attack, a single-input-single-output control law was employed successfully at constant gain throughout the entire angle of attack range without requiring adaptations.

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