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Experimental Evaluation of an Advanced Buffet Suppression System on Full-Scale F/A-18 Fin

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Buffeting is an aeroelastic phenomenon that plagues high-performance aircraft, especially with those with twin vertical tails such as the F/A-18. At high angles of attack, unsteady vortices that emanate from wing leading-edge extensions interact with the vertical fin, resulting in premature fatigue failure. An advanced hybrid buffet suppression system was experimentally evaluated on a full-scale F/A-18 empennage as an international technical collaboration activity among Australia, Canada, and the United States under the auspices of The Technical Cooperative Program. The advanced hybrid buffet suppression system incorporated two distinct actuation systems to control the bending and torsion modes independently. The vertical fin bending mode was counteracted using the inertial loading from the rudder structure while the first torsion model was controlled using surface-mounted macrofiber composite conformable actuators optimally located on the fin. The buffet excitation input generated by the shakers matched the buffet modes and magnitude expected under aerodynamic loading, but it was difficult to match the aerodynamic damping. Therefore, closed-loop tests were conducted under two damping conditions that were lower and higher than the expected aerodynamic damping level. The lower damping condition was produced by imposing free vibration condition on the active fin, and the higher damping condition was tested using forced vibration. The real-time adaptive controllers were able to effectively suppress both the bending and torsion vibration modes under representative buffet load spectra. The performance of the hybrid actuation system was significantly greater at the low damping condition, which led to higher reduction in vibration. Results showed that the conventional rudder and macrofiber composite actuator systems were capable of simultaneously reducing both the bending and torsion modes sufficiently to double the fatigue life of the fin. The full-scale closed-loop tests demonstrated that the advanced hybrid buffet suppression system is a feasible solution to alleviate vertical tail fatigue due to buffeting in fighter aircraft.

I. Introduction

THE F/A-18 is a an extremely versatile high-performance tactical fighter jet that was designed to achieve both unrestricted angle-of-attack (AOA) performance and maneuverability in all corners of the aircraft operational envelope. These design goals were achieved by the unique blend of high-lift devices, the leading-edge extension, carefully positioned horizontal and vertical tail surfaces, and effectively blended digital flight control laws. In particular, the inner wing leading-edge extension (LEX) provides fuselage lift that enables the aircraft to achieve high AOA in excess of 60 deg. The twin vertical tails canted slightly outward exploit the high-energy vortices generated by each LEX to provide good directional stability at these high-AOA conditions. Unfortunately, these unique capabilities generate undesirable side effects caused by placing the horizontal and vertical surfaces in the wake of the LEX vortex that breaks down upstream of the vertical tails at high AOA, as shown in Fig. 1. This vortex energy leads to an aeroelastic phenomenon known as buffeting, which excites structural resonance frequencies of the empennage to generate dynamic stresses [1]. In addition, the empennage response excites engine and other aft fuselage components, causing high stress levels in various structural components throughout the aircraft during maneuvers inside the operational envelope. The impact of this aeroelastic behavior on the vertical tail was first observed early in the service deployment of the F/A-18A/B aircraft when cracks were discovered on the root stub structure. Investigations revealed that prolonged exposure to buffeting led to fatigue damage of the vertical fin, and a special inspection was recommended every 200 flight hours to monitor structural damage due to buffet loads [2].

Previous flight trials and wind tunnel tests have shown that a significant portion of the fatigue damage on the vertical fins was caused by stresses resulting from the first bending and first torsion vibration modes of the vertical fin. The frequency content and the intensity of the fin buffet load vary primarily as a function of AOA and the dynamic pressure (Q) [3]. Typical air combat maneuvers involve rapid variations in AOA-Q conditions with peak vibration levels occurring in different AOA-Q ranges. At low AOA, between 24 and 28 deg, the vortices impinged on the lower portion of the vertical fin. The broadband buffet load excited both the first bending mode at 15 Hz and the first torsion mode around 45 Hz. However, the broadband excitation predominately increased the response of the first torsion mode, causing damage in the upper portion. At these AOAs, the aft tip peak acceleration was over 300 g at 45 Hz, whereas the dynamic pressure was in the range of 400–500 psf [4]. At high AOA, around 32–36 deg, the vortices impinged on the upper portion of the fin, increasing the amplitude of the first bending mode at 15 Hz. This resulted in a significant increase in damaging stresses at the fin root, particularly on the fuselage and vertical tail attachment stubs. At these high AOA, the aft tip peak acceleration was over 170 g at 15 Hz, whereas the dynamic pressure was in the range of 175–225 psf. The collected buffet vibration spectra from flight tests represented the general envelope of flight conditions experienced by the fleet during normal operation. The flight tests also revealed that the amount of time that the operational aircraft actually spends on these conditions decreased as the angle of attack increased.

Designing the vertical fin structure to withstand these intense vibration loads generated by aeroelastic buffet conditions is a

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Fig. 1 Vortices breakdown upstream of the vertical fin.

challenging task. Therefore, several approaches have been investigated to alleviate the buffet load damage on the vertical fins of the aircraft. Currently, limited reduction in buffet loads is achieved by flow control and structural modification techniques. The flow control approach aims to modify the vortical flowfields to reduce the intensity of buffet loads. For example, a rigid fence had been installed on the upper surface of the F/A-18 LEX to disperse the vortices before impinge on the vertical fin [5]. In addition to the aerodynamic penalty, the LEX fence provided only limited reduction in buffet load and it was effective only at specific flight conditions. Moreover, the additional vortices generated by the LEX fence may break down at higher angles of attack, leading to more turbulent wakes [6].

The structural modification approach tries to alter the load-carrying structures on the vertical tail. For example, the stiffness of the F-15 vertical fin structure was increased by incorporating composite brackets, doublers and cleats, thicker skin, and spars [7]. However, these modifications resulted in a significant increase in structural weight as well as transfer of the dynamic loads, and therefore increasing potential damage to structural components elsewhere. Because passive techniques do not substantially mitigate the buffeting problem, recent activities have been focused on controlling structural response using active buffet load alleviation techniques [8]. The active approaches provide multiple mode response reduction capability as well as optimized performance for varying flight conditions.

The problem of vertical tail buffeting is a particular concern for Canada, Australia, and the United States because the F/A-18 aircraft is part of their air force fleet [9]. To find an adaptive solution to alleviate the F/A-18 vertical fin responses, a collaborative research project was initiated under the auspices of The Technical Cooperative Program (TTCP). The objective of this TTCP project was to design, develop, and demonstrate a smart structure-based buffet load alleviation system on a full-scale F/A-18 vertical tail [10]. The participation and contribution to the F/A-18 buffet load alleviation project under TTCP was defined through an international project arrangement signed between defense departments of the United States, Australia, and Canada. The organizations involved in this multiyear research project were the National Research Council Canada (NRCC), Department of National Defence (DND) from Canada, the Air Force Research Laboratory (AFRL) from the U.S., NASA Langley Research Center (NASA LaRC) from the U.S., the Defence Science and Technology Organisation (DSTO) from Australia, and the Boeing Company from the U.S. This paper discusses the performance of the full-scale F/A-18 buffet suppression system using the real-time controller developed and implemented by the Canadian team of investigators from the National Research Council Canada.

II. Advanced Hybrid Buffet Suppression System for the F/A-18 Vertical Tail

The advanced hybrid buffet suppression system developed by the Boeing Company, U.S. Air Force Research Laboratory, and NASA LaRC for the full-scale F/A-18 vertical fin incorporated two distinct actuation systems [11] to control the bending and torsion modes independently as depicted in Fig. 2. The vertical fin bending mode, which generated the most destructive buffeting energy at the root, was counteracted using the inertial force of the rudder structure. This was achieved by using a conventional F/A-18 rudder actuator shown in Fig. 3 in a push and pull manner at a rate of nominally 15 Hz, corresponding to the fin bending mode. The strain gauges were bonded to the root stubs of the fin to measure dynamic strain under simulated buffet load excitation spectra. Under the regulation of a closed-loop control law based on strain gauge sensor data, this approach was expected to suppress the critical stresses due to the bending mode at the root of the vertical fin. This high-frequency displacement of the rudder was not expected to generate sufficient aerodynamic loads to interfere with the quasi-static rudder movements required for aircraft yaw control.

Torsion modal strain energy is primarily located in the upper portion of the fin structure. Because of the relatively low amplitude of the vibration at the high torsional frequency of 45 Hz, piezoelectric actuators developed by NASA LaRC were surface mounted to control the torsional mode. The unidirectional piezoelectric patch actuators, known as macrofiber composites (MFC), were placed at optimal areas of the vertical fin based on maximum dilatational strain energy distribution criteria as shown in Fig. 3. The MFC actuators were bonded on both sides of the fin, and actuators on each side were connected to operate out of phase to maximize control authority [12]. Based on characterization tests conducted by NASA LaRC and Boeing, nine layers of 0.18 mm thick MFC actuators were stacked to provide sufficient strain actuation to control the torsional mode [13]. The accelerometer attached to the aft tip of the vertical fin shown in Fig. 2 was used to measure the torsional response of the structure. The closed-loop controller generated the appropriate control voltage

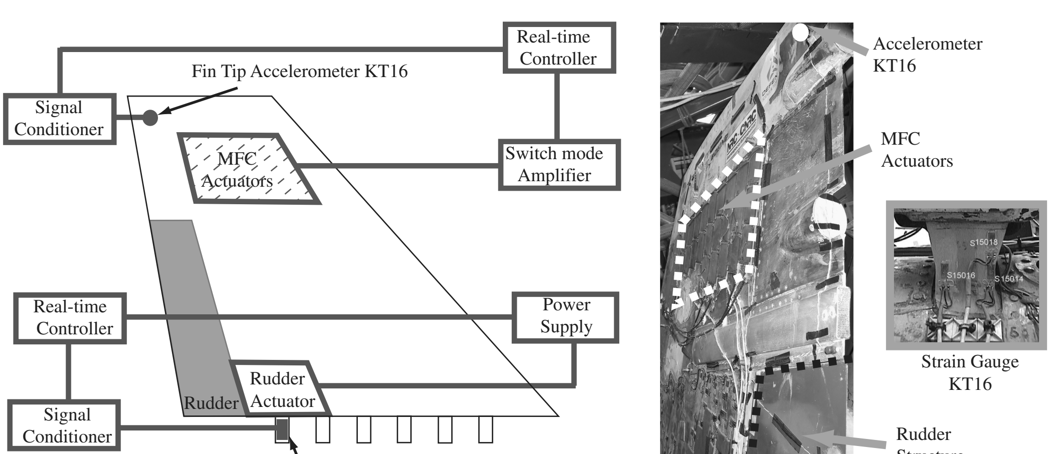
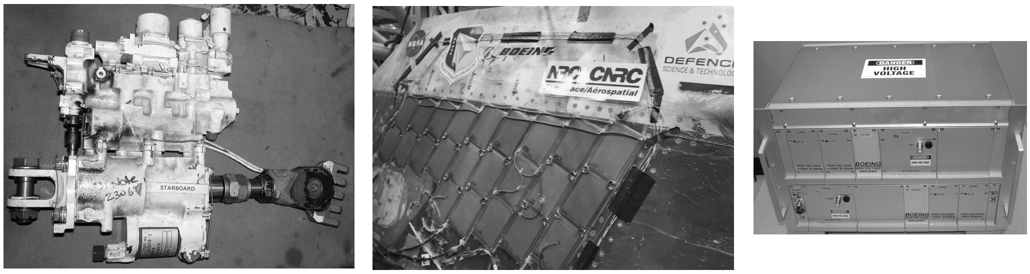


Fig. 2 Advanced hybrid buffet load alleviation system.



Conventional Rudder Actuator Conformable MFC Actuators Switch Mode Amplifiers

Fig. 3 Hardware components of the hybrid buffet load alleviation system.

to the MFC actuators based on the sensor data from the accelerometer. Efficient high voltage switch mode amplifiers rated as 3.0 kilovolt peak-to-peak (kVpp) at 2 A were specifically designed by the Boeing Company to power the MFC actuators. These highly efficient switch mode amplifiers shown in Fig. 3 were smaller in size and lighter in weight than similarly rated linear amplifiers because they accounted for the reactive load of piezoceramic actuators.

III. Full-Scale Experimental Test Setup

The full-scale F/A-18 vertical tail ground vibration test was conducted using the International Follow-On Structural Testing Project (IFOSTP) facility at the DSTO in Melbourne, Australia. The hybrid active buffet load suppression system using the rudder and MFC actuators was instrumented on the starboard fin of the test article in the IFOSTP test rig shown in Fig. 4.

A. Real-Time Adaptive Controller

Extensive closed-loop tests were conducted using the full-scale experimental setup to evaluate performance of the advanced hybrid actuation system under representative buffeting load levels with several real-time adaptive controllers developed by the participating organizations. This paper discusses the performance of the full-scale F/A-18 buffet suppression system using the real-time controller developed and implemented by the Candian team of investigators from the National Research Council Canada. The strain gauge at the trailing-edge root stub, labeled S15016, was selected as the error sensor to control the bending mode because it corresponded to the most critical location of stress introduced by the bending mode. The accelerometer located at the aft tip of the starboard fin, labeled KT16, was used as the error sensor for the MFC actuators to control the torisonal mode because it was sensitive to the modal displacment. A Linear Quadratic Gaussian (LQG) regulator was chosen for the real-time control algorithm due to its advantages in balancing performance and control effort, as well as the capability to take process and measurement noise into account. Two independent LQG controllers were developed for the rudder and MFC plants to suppress both bending and torsional modes simultaneously. The controller for the rudder plant was designed to minimize the strain at the aft root stub, whereas the controller for the MFC plant was designed to minimize the aft tip acceleration of the starboard fin. The details of LQG control law, which consisted of a full-state regulator in series with a Kalman state estimator, are described in [14]. The LQG controller was implemented in real time on the full-scale F/A-18 empennage using Matlab/Simulink software and an xPC Target hardware platform. This digital signal processing system allowed rapid algorithm prototyping and hardware-in-the-loop experiment for efficient implementation and optimization of real-time control parameters.

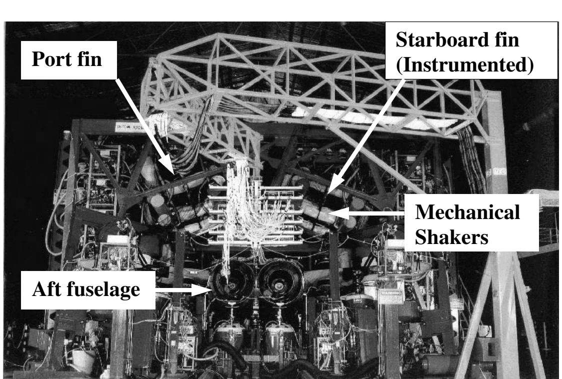


Fig. 4 IFOSTP test rig at DSTO in Melbourne, Australia.

B. Buffet Excitation Conditions

The IFOSTP test rig has the ability to generate flight representative static and dynamic loads on the full-scale vertical tail structure using two 5000 lbf electrodynamic shakers attached to each vertical fin. Multiple dynamic load spectra were developed for the fin excitation by analyzing the vertical fin response data from flight tests conducted by the Department of National Defence Canada on a CF-18 aircraft [15], to simulate the buffet loads in the ground test. In particular, one excitation load spectrum was designed to induce maximum overall damage, and another spectrum generated the maximum response under buffet loads. The load spectrum of interest for this work was the maximum damage excitation spectrum, which represented the worst fatigue damage condition of the entire vertical fin structure.

For the maximum damage spectrum, the buffet load was nominally applied by using two narrow frequency bands, namely, band 1 of 10–20 Hz that enveloped the bending mode frequency and band 2 of 34–52 Hz that enveloped the torsional mode frequency. To provide representative maximum damage buffeting conditions to the fin, two load cases were developed. The buffet load case 1 was primarily designed to excite the bending mode and the buffet load case 2 to excite the torsional mode. However, it is important to note that both load cases contained considerable broadband frequencies that covered both modes. To provide an incremental load to the hybrid buffet load alleviation system, each load spectrum was scaled to four levels of the maximum excitation, namely, 25, 50, 75, and 100%. The shaker input spectra for buffet load cases 1 and 2 are shown in Fig. 5.

C. Damping Conditions

The buffet excitation input generated by the electrodynamic shakers matched buffet modes and magnitude expected under aerodynamic loading conditions, but it was difficult to match the aerodynamic damping due the inertia of the attached shakers. Baseline response spectra measured by the KT16 accelerometer on the active starboard fin while applying the incremental levels of buffet excitation on the same fin are shown in Fig. 6. As expected, the buffet load case 1 primarily excited the bending mode, whereas the buffet load case 2 primarily excited the torsional mode. The peak vibration amplitudes measured by accelerometer KT16 for the baseline buffet load cases are shown in Table 1. Note that the maximum buffet level for both buffet load cases could not be performed under forced vibration condition to test rig safety concerns when the shakers attached to the starboard fin were driven at 100% excitation level. Although the forced vibration of the active fin matched the structural modes and vibration amplitudes expected

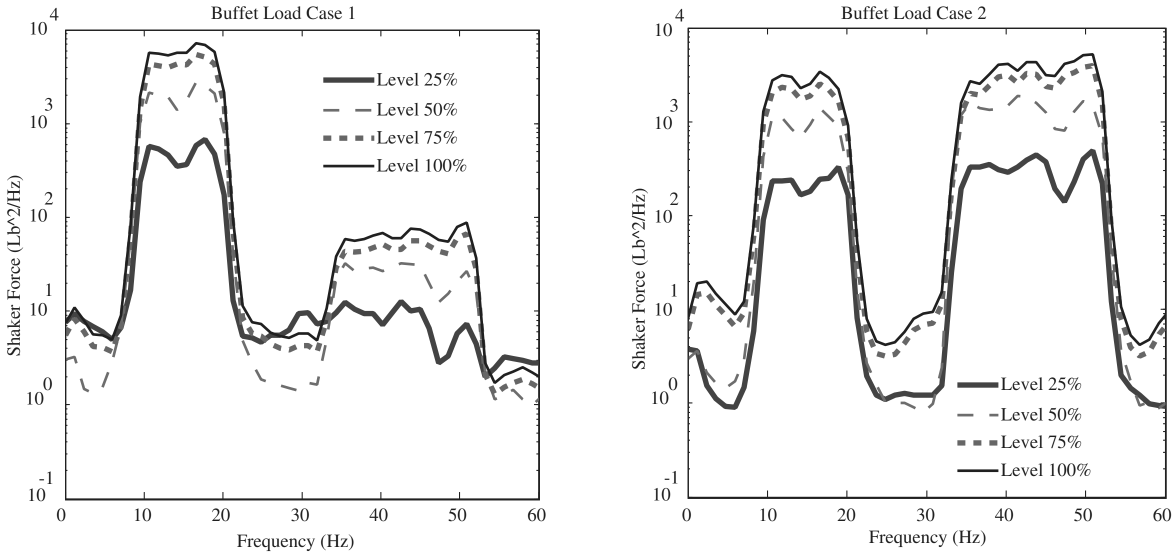


Fig. 5 Buffet load excitation spectra for the buffet load case 1 and buffet load case 2.

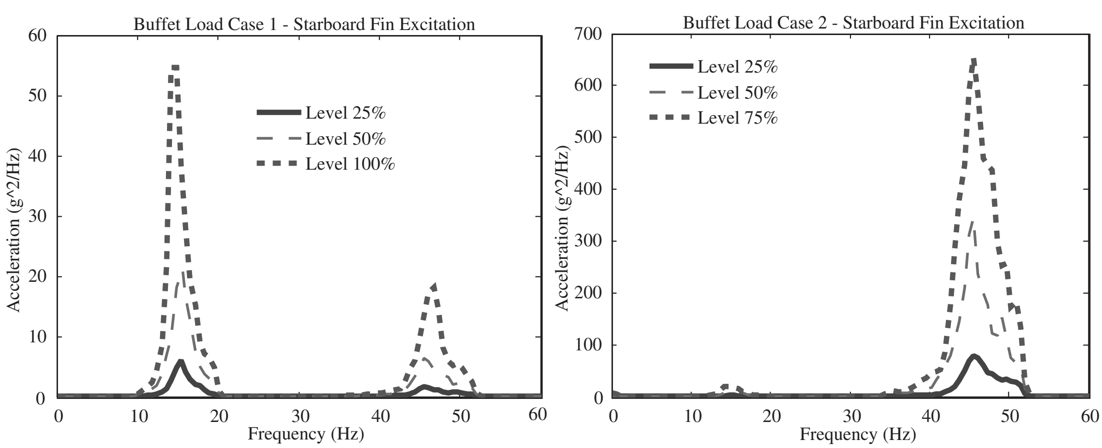


Fig. 6 Accelerometer KT16 response for starboard fin excitation.

under buffet conditions, the damping of these modes increased significantly due to the mass of the attached shakers. To experimentally determine the damping ratio for the bending mode, a swept sinusoidal signal from 5 to 25 Hz was applied to the rudder actuator on the starboard side fin. Simultaneously, the mechanical shakers attached to the active fin were energized with a low-amplitude buffet excitation spectrum that corresponded to 10% of buffet load case 2 to represent the dynamic mass of shakers. Similarly, the damping associated with the torsional mode was determined by sweeping a sinusoidal signal from 40 to 55 Hz to drive the MFC actuators while the shakers were energized with a low-amplitude excitation spectrum that corresponded to 10% buffet load case 1. High damping ratios of 10 and 15% were observed for the bending and torsional modes, respectively, due to the effect of additional dynamic mass from the heavy shakers attached to the active fin. High damping associated with the two primary modes on the full-scale F/A-18 fin was expected to deteriorate the vibration suppression performance of the advanced hybrid active system.

To evaluate the performance of the hybrid actuation system under lower damping condition, the excitation buffet spectra was applied to the port fin while the shakers on the active fin were detached. Excitation of the port fin transmitted the vibratory loads to the active fin through the empennage, resulting in free vibration condition. However, load transmission through the F/A-18 empennage resulted in lower buffeting input levels to the active fin as shown in Fig. 7. The analysis of the vibration response of the accelerometer KT16 showed that approximately 40 and 42% of the vibration energy of the bending mode was transmitted for buffet load cases 1 and 2, respectively. A

Table 1 Peak vibration measured by the accelerometer KT16 during baseline buffet excitations

Excitation condition	Incremental load level	Bending mode peak, g^2/Hz		Torsion mode peak, g^2/Hz	
		Buffet load case 1	Buffet load case 2	Buffet load case 1	Buffet load case 2
Forced vibration (high damping)	Level 25%	4.73	2.61	1.42	70.46
	Level 50%	19.92	9.49	5.41	284.36
	Level 75%	45.79	17.69	15.71	579.39
Free vibration (low damping)	Level 25%	1.64	0.79	0.04	0.15
	Level 50%	3.94	2.81	0.08	0.42
	Level 75%	9.64	4.09	0.16	0.89
	Level 100%	15.53	9.35	0.37	1.44

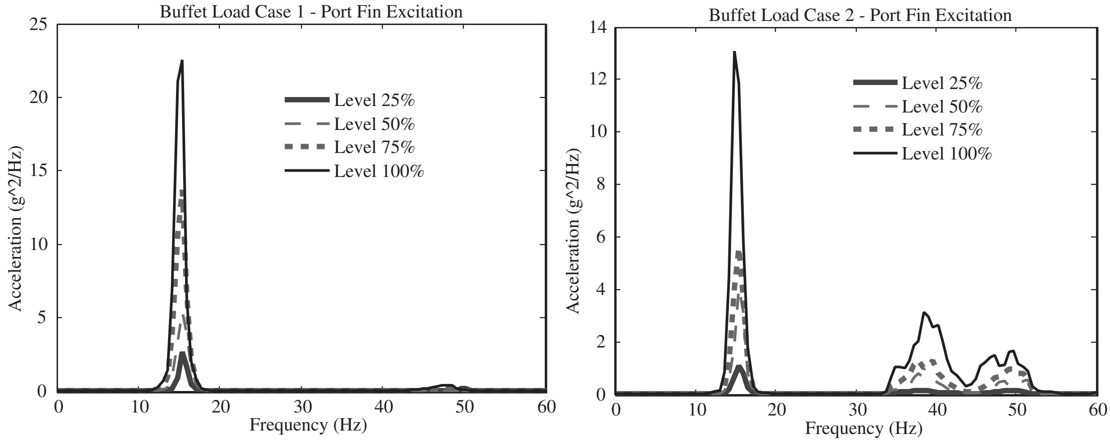


Fig. 7 Accelerometer KT16 response for port fin excitation.

much lower vibration energy transmission rate was observed for the torsion mode due to the high-frequency filtering effect of the aft fuselage structure. Approximately 4 and 12% of torsional vibration energy was transmitted for buffet load cases 1 and 2, respectively. As expected, the free vibration test condition reduced the damping associated with each structural mode because the shakers were detached from the fin instrumented with the hybrid active system. These damping ratios were calculated by sweeping the actuator systems on the active fin at appropriate frequency ranges, whereas the mechanical shakers excited the port fin with low-amplitude excitation. Much lower damping ratios of 6 and 4% were calculated for the bending and torsional modes, respectively, in free vibration test condition. The level of damping was much lower compared to the forced vibration test condition, and the aerodynamic damping level is expected to be in between these two high and low damping levels encountered during full-scale ground vibration tests. Thus, the full-scale closed-loop control tests were conducted under two damping conditions using forced vibration and free vibration test conditions on the active fin.

IV. Controller Performance Evaluation

Although several buffeting load excitation spectra were used during closed-loop tests, the ones of most interest were the maximum damage buffet excitation load cases. Under the control of a LQG regulator, the advanced hybrid actuation system alleviated the fin vibration effectively under the maximum damage excitation load spectra to significantly reduce the fin response. The LQG controller demonstrated robustness under all tested buffeting load cases and levels. Both the bending and torsional structural modes were suppressed effectively and simultaneously. The buffet load alleviation performance of the advanced hybrid buffet suppression system was evaluated by analyzing the response of the full-scale fin structure using the peak reduction of the bending and torsional modes measured by the accelerometer KT16 located on the aft fin tip. Percentage reductions of each vibration peak measured during closed-loop control tests under both damping conditions are summarized in Table 2.

A. Forced Vibration Condition

Typical closed-loop control results measured by the fin tip accelerometer KT16 for buffet load case 1: level 25% under the forced vibration condition are shown in Fig. 8. Although the forced vibration condition generated representative response amplitudes for both modes, high damping due to attached shakers degraded the performance of the hybrid control system substantially. The bending mode peak suppression varied from 28 to 8% and the torsion mode peak suppression varied from 78 to 43% as the buffet load case 1 was increased from 25 to 75% level. Under the forced vibration condition, the peak vibration suppression performance increased for the bending mode and decreased for the torsion mode when buffet load case 2 was applied to the active fin. This is because the buffet load case 2 spectrum increased the excitation level of the torsional mode and decreased the excitation level of bending mode.

Further analysis of the closed-loop results showed that both the rudder and the MFC actuator systems saturated under high buffet excitation conditions. The rudder actuator saturated at 1 deg peak-to-peak deflection under high control voltages, which limited the effect of rudder inertial load to a maximum value at saturation. Therefore, increased displacement of the fin structure due to higher excitation loads was counteracted by a limited maximum inertia force due to rudder actuator saturation. Accordingly, the percentage of vibration suppression was reduced at higher buffet excitation levels. The amount of vibration reduction could be increased with a rudder actuator with a broader operating frequency bandwidth, which would saturate at a larger deflection resulting in greater inertial forces. Similarly, the voltage input to the MFC actuators was limited to 1500 V peak-to-peak due to output limitation of power amplifiers. Increase in upper voltage limits or using piezoceramic materials with higher actuation coefficient could delay saturation to improve the system performance significantly.

B. Free Vibration Condition

The performance of the advanced hybrid buffet suppression system in both modes increased under the free vibration test condition with shakers detached from the active fin. The lower damping level compared to the forced vibration condition led to a

Table 2 Percentage vibration reduction measured by KT16 accelerometer during closed-loop LQG control

Excitation condition	Incremental load level	Bending mode peak		Torsion mode peak	
		Buffet load case 1	Buffet load case 2	Buffet load case 1	Buffet load case 2
Forced vibration (high damping)	Level 25%	28%	36%	78%	22%
	Level 50%	13%	31%	51%	15%
	Level 75%	8%	28%	43%	12%
Free vibration (low damping)	Level 25%	85%	91%	92%	73%
	Level 50%	73%	82%	70%	62%
	Level 75%	55%	73%	55%	52%
	Level 100%	45%	68%	35%	29%

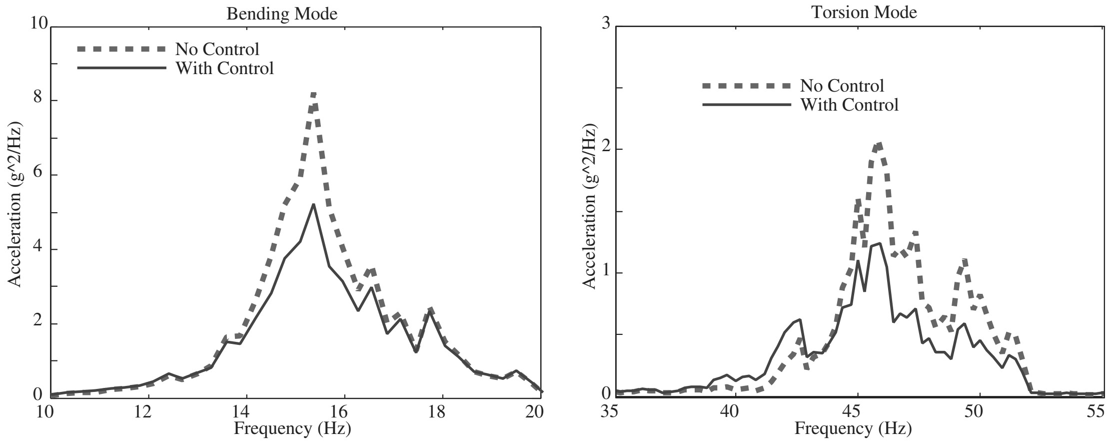


Fig. 8 Hybrid system performance measured using accelerometer KT16 for forced vibration condition (buffet load case 1: level 25%).

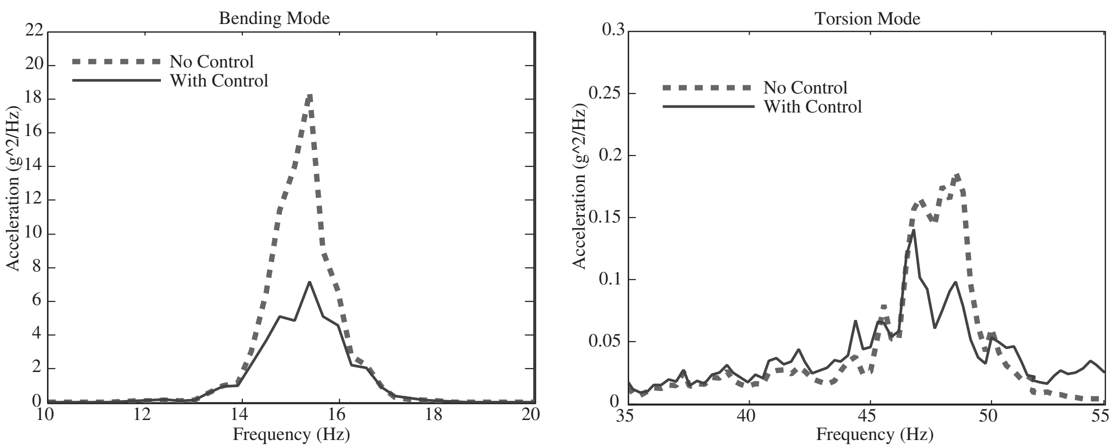


Fig. 9 Hybrid system performance measured using accelerometer KT16 for free vibration condition (buffet load case 1: level 75%).

substantial increase in the vibration reduction performance of the hybrid active system. Typical closed-loop control results measured by the fin tip accelerometer KT16 for buffet load case 1: level 75% under the free vibration condition are shown in Fig. 9. The bending mode peak suppression varied from 89 to 41% and the torsion mode peak suppression varied from 92 to 35% as the buffet load case 1 was increased from 25 to 75% level. The peak vibration suppression performance was increased for the bending mode and decreased for the torsion mode when buffet load case 2 was used for excitation because the input spectrum increased the torsional mode and decreased the bending mode. It is important to note that the transmission of vibratory loads from port to starboard fin under free vibration condition resulted in a lower baseline buffeting response levels on the active fin. This significantly reduced the amplitude of the torsion mode, which resulted in a larger percentage decrease in the vibration suppression because the capability of actuators remained constant.

V. Discussion

Although numerous buffet load cases and levels were used successfully to demonstrate the performance of the advance hybrid buffet load alleviation system on a full-scale F/A-18 vertical tail structure, the maximum buffet excitation level for both modes was not tested due to test rig safety concerns. In addition, closed-loop tests were performed under two distinct damping conditions generated on the fin structure through forced and free vibration conditions because the level of damping under aerodynamic loads could not be achieved during ground vibration tests. The hybrid actuation system demonstrated actuation authority throughout all tested maximum damage buffeting load excitations. Therefore, the performance of the active system was extrapolated to estimate the vibration suppression performance at the maximum buffet load level under aerodynamic damping condition. The extrapolation technique assumed that the energy available in each active control system to counteract the vibration was a constant. The vibration reduction measured for the bending and torsion modes using the experimentally evaluated active system are shown in Fig. 10 along with the extrapolated performance for the 100% buffet excitation level. The input buffet load levels were normalized by the maximum vibration amplitude expected for each mode at the 100% excitation level to combine the closed-loop control results from forced vibration and free vibration test conditions.

The closed-loop vibration suppression performance extrapolated for the 100% buffet excitation predicted a suppression of 21 and 7% of the bending mode peak using the rudder actuation system under free and forced vibration conditions, respectively. However, the aerodynamic damping level was expected to be significantly lower than the 10% damping level corresponding to the forced vibration condition while marginally higher than the 6% damping level measured under the free vibration for the bending mode. Therefore, it was estimated that active rudder system would reduce over 10% of the bending mode peak at 100% buffet excitation under aerodynamic conditions.

Similar extrapolation for the 100% excitation level of the torsional mode indicated that 10% reduction in the torsion mode peak was expected under forced vibration condition. Closed-loop vibration suppression results for the torsional mode from the free vibration condition could not be used with confidence to extrapolate the 100% level because the highest response corresponded to only 12% of the maximum. However, suppression of the torsion vibration peak using MFC actuators is expected to be over 10% because aerodynamic damping is significantly lower than 15%, which was measured for the torsional mode under forced vibration condition.

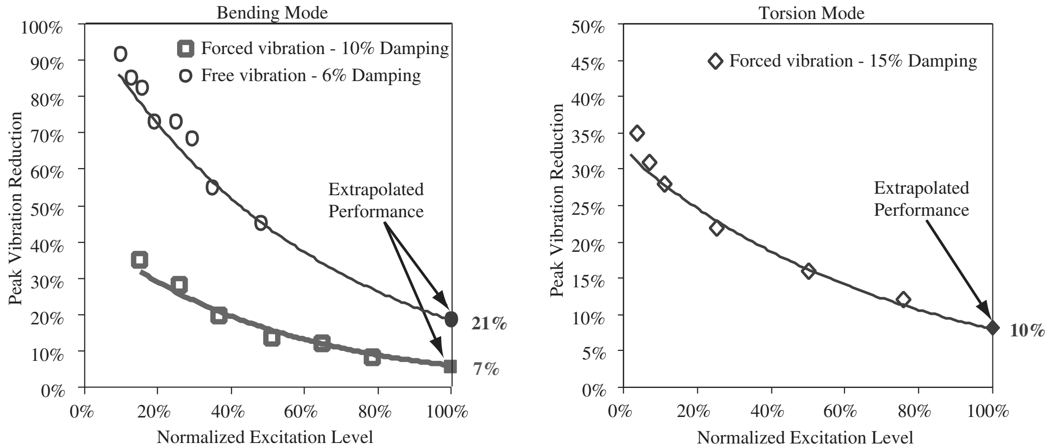


Fig. 10 Extrapolated performance of the advanced hybrid buffet suppression system.

It is important to note that the objective of the advanced hybrid buffet load suppression system was not to achieve a full reduction of the vibration amplitude of either mode but rather to achieve a reduction in amplitude of the primary vibration peaks, particularly the bending mode, to sufficiently reduce the maximum strain in the critical areas of the fin structure to improve fatigue life. According to the analytical results, a 10% reduction in primary vibration peaks is predicted to reduce the peak stress on the F/A-18 empennage to double the fatigue life of the fin structure [16].

The full-scale closed-loop tests demonstrated that the inertia of the rudder structure and MFC actuators were able to suppress the bending and torsion modes effectively. The demonstrated active control of the rudder system is more easily implemented on high performance aircraft plagued with the buffet phenomenon because the system uses the conventional rudder actuator. The active rudder system could suppress the fin bending mode, which is the primary structural mode that generates the most destructive buffeting energy at the root. Implementation of the active rudder system only requires the control software to be modified with a real-time adaptive algorithm to regulate the rudder actuator in an adaptive manner. The implementation of the MFC actuator system to control the torsion mode may require substantial development. The reliability, safety, and durability of the piezoceramic actuator system needs to be verified through extensive tests. In addition, the switch mode amplifiers require further miniaturization to reduce the weigh and the size to be installed in fighter aircraft.

VI. Conclusions

This paper presented the experimental evaluation of the full-scale advanced hybrid buffet suppression system for the F/A-18 vertical tail structure. The hybrid actuation system employed a hydraulic rudder actuator and distributed MFC piezoelectric actuators to control the first bending mode and first torsional mode independently and simultaneously. The vertical fin bending mode was counteracted using the inertial loading from the rudder structure, whereas the first torsion model was controlled using surface- mounted MFC actuators optimally located on the fin. The buffet excitation input generated by the shakers matched the buffet modes and magnitude expected under aerodynamic loading, but it was difficult to match the aerodynamic damping. Therefore, closed-loop tests were conducted under two damping conditions that were lower and higher than the expected aerodynamic damping level. The lower damping condition was produced imposing a free vibration condition on the active fin, and the higher damping condition was tested using forced vibration. The real-time adaptive controllers were able to effectively suppress both the bending and torsion vibration modes under representative buffet load spectra. The performance of the hybrid actuation system was significantly greater at the low damping condition, which led to higher reduction in vibration. Results showed that the conventional rudder and MFC actuator systems were capable of simultaneously reducing both the bending and torsion modes sufficiently to levels that are predicted to double the fatigue life of the fin. The demonstrated active rudder control system could be implemented more easily on high performance aircraft because the system uses the conventional rudder actuator, whereas implementing the MFC actuator system may require further development. The full-scale closed-loop tests demonstrated that the advanced hybrid buffet suppression system is a feasible solution to alleviate vertical tail fatigue due to buffeting in fighter aircraft.

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