Actively Controlling Buffet-Induced Excitations

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ABSTRACT

High performance aircraft, especially those with twin vertical tails, encounter unsteady buffet loads when flying at high angles of attack. These loads result in significant random stresses, which may cause fatigue damage leading to restricted capabilities and availability of the aircraft. An international collaborative research activity among Australia, Canada and the United States, conducted under the auspices of The Technical Cooperation Program (TTCP) contributed resources toward a program that coalesced a broad range of technical knowledge and expertise into a single investigation to demonstrate the enhanced performance and capability of the advanced active BLA control system in preparation for a flight test demonstration. The research team investigated the use of active structural control to alleviate the damaging structural response to these loads by applying advanced directional piezoelectric actuators, the aircraft rudder, switch mode amplifiers, and advanced control strategies on an F/A-18 aircraft empennage. Some results of the full-scale investigation are presented herein.

1.0 INTRODUCTION

Buffeting is an aeroelastic phenomenon that is common to high performance aircraft, especially those with twin vertical tails like the F/A-18 (Figure 1), at high angles of attack [1-7]. These loads result in oscillatory stresses and strains (Figure 2), which may cause significant fatigue damage leading to restricted capabilities and availability of the aircraft. Because of the importance of this topic to many fleets around the world, an international collaborative research activity among Australia, Canada and the United States was formed to investigate the use of active structural control to alleviate damaging structural response to these loads. The research program is co-ordinated by the Air Force Research Laboratory (AFRL) and conducted under the auspices of The Technical Cooperative Program (TTCP). This truly unique collaborative program is developed to enable each participating country to contribute resources toward a program that unites a broad range of technical knowledge and expertise into a single investigation, directed toward a full-scale test of an F/A-18 empennage [8]. This full-scale test was conducted in the Australian International Follow-On Structural Test Program (IFOSTP) test rig, located at DSTO, using a structural test article shown in Figure 3.

Figure 1. Vortices from the leading edge of a twin-tail fighter aircraft, generated at high angles of attack, breakdown upstream of the empennage.

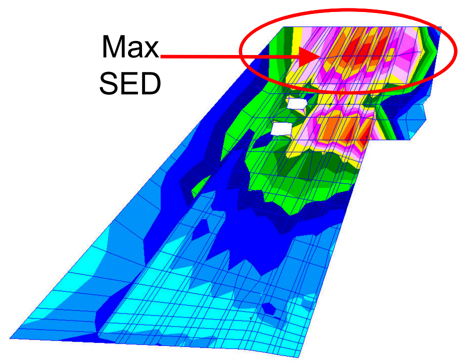

Figure 2. Surface strain energy density (SED) for the 2nd resonant mode (1st torsion mode) of the fin.

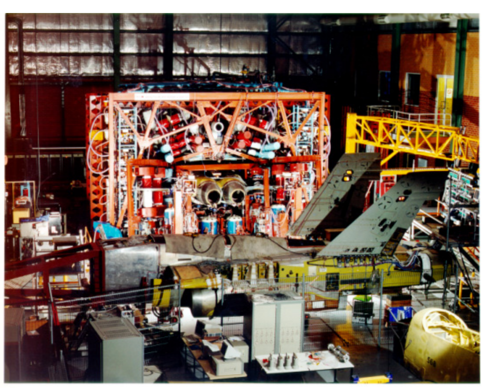

Figure 3a. Rig with one F/A-18 structural test article inserted and another in the foreground

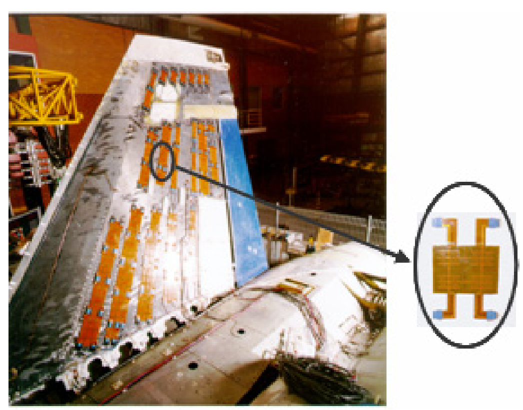

Figure 3b. F/A-18 structural test article with former piezoelectric actuator design

This program is the extension of earlier wind-tunnel tests [9-11] and a full-scale demonstration [12-15]. Using scaled hardware, similar actuators and control law strategies, a prior wind-tunnel test (Figure 4) examined the combination of simultaneous rudder and piezoelectric actuator controls to suppress vibratory motion of the tail when buffeted [15-16]. Illustrated in Figure 5, the rudder and piezoelectric actuators control vibratory motions in different frequency bands, by design. In most cases, the hydraulics and servomechanism of the rudder inhibit its effectiveness to control vibratory motion of the tail at frequencies above 20 Hertz [17].

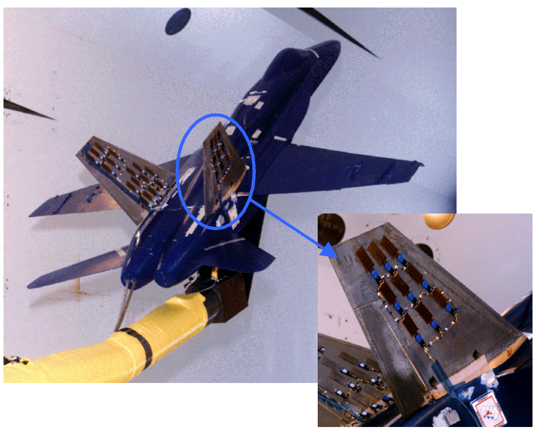

Figure 4. 1/6-scale F/A-18 Model with active rudder and piezoelectric actuators in the Transonic Dynamics Tunnel at the NASA Langley Research Center

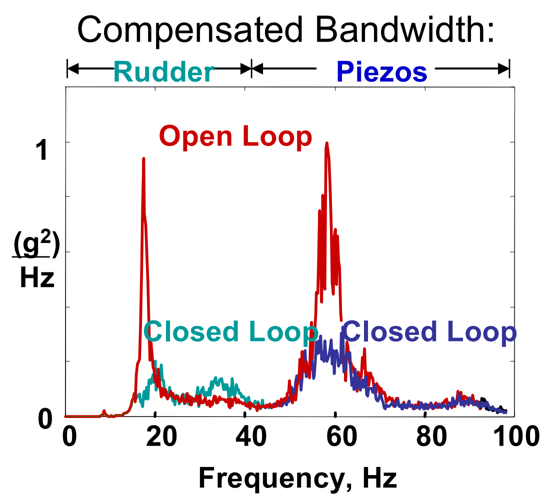

Figure 5. Typical Active Buffet Load reduction through feedback control loops of the rudder and of the MFC actuators on wind-tunnel model.

Piezoelectric actuators are not constrained by these limitations and maintain effectiveness at much higher frequencies, as illustrated in Figure 5. A former generation of piezoelectric actuators (Figure 3b) were tested on the F/A-18 aircraft empennage during the prior program [12-15]. Although effective in mitigating buffet loads, those piezoelectric actuators and their control electronics did not offer a suitable design for aircraft integration leading to a flight test [18].

The current full-scale test program used the rudder of the aircraft, and advanced piezoelectric actuators and amplifiers in an optimized capacity to demonstrate performance and capability of the buffet load alleviation system in preparation for a flight test demonstration [19]. This paper presents the controls designs and performances based on the strategies explored by members of the multi-national team.

2.0 SYSTEM CONCEPT

A significant portion of the modal strain energy in the 2nd mode (Figure 2) was in the skin of the upper third portion of the fin where the surface mounted piezoceramic actuators were located and where their effectiveness was relatively significant due to the relatively low structural stiffness in this region. By contrast, a significant portion of the modal strain energy in the fundamental bending mode occurred near the root of the fin, where the piezoceramic actuators were not as effective due to the significant structural stiffness in this region. However, the rudder was quite effective in this case [10, 17, 20]. Therefore a rudder-piezo actuator "blended" BLA system was investigated experimentally on a 1/6-scale F/A-18 model installed in the

Transonic Dynamics Tunnel at NASA LaRC [11]. The program undertaken by NASA LaRC and Boeing used neural predictive controllers [16] as well as time-invariant control laws [11] for controlling the rudder, for the first bending, and piezoactuators, for the torsion mode, of the starboard-side fin. This study was followed by a theoretical analysis on a rudder-piezo "blended" system, as shown schematically in Figure 6, and showed 'on paper' the feasibility of such an advanced active BLA control system on a full-scale structure [21]. The theoretical study also gave an indication of (1) the maximum command rudder position, (2) the number and position of the directional piezoactuators and (3) peak power levels required for the full-scale tests. The study also showed that the primary control force was the rudder inertial force and not the aerodynamic force. Hence the follow-on ground test program investigated active control of the rudder control surface to control the 1st resonant mode and directional piezoceramic actuators powered by switch mode amplifiers to control the 2nd resonant mode.

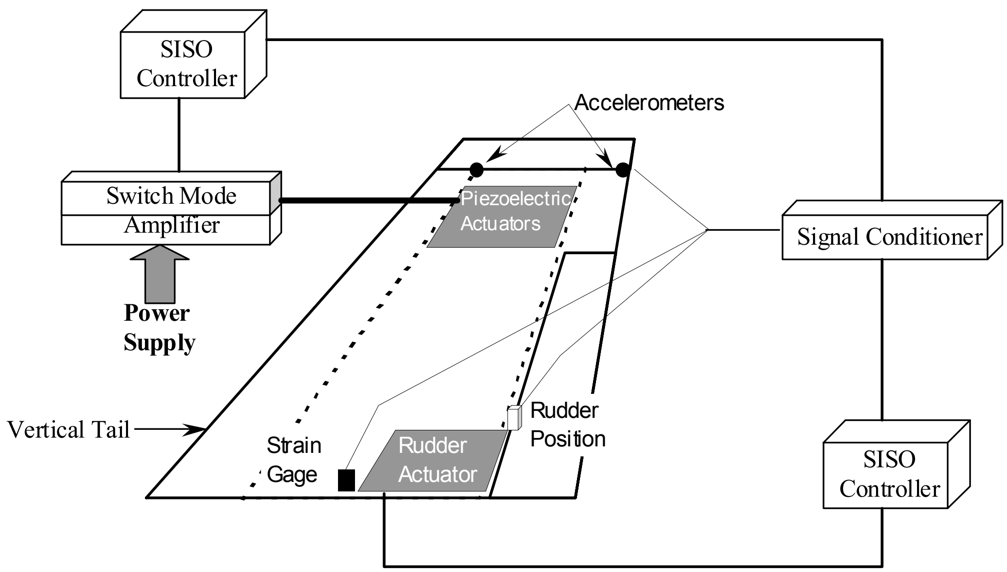

Figure 6 Major Components of BLA System

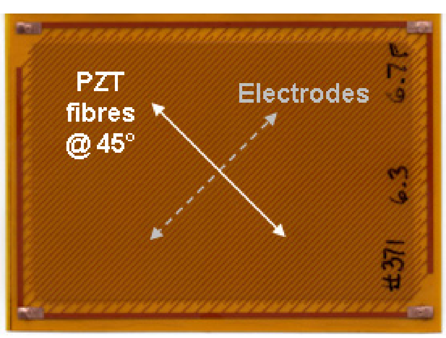

Figure 7. NASA LaRC MFC actuator for the Buffet Load Alleviation (BLA) testing program, interdigitated electrodes and piezoceramic fibers shown.

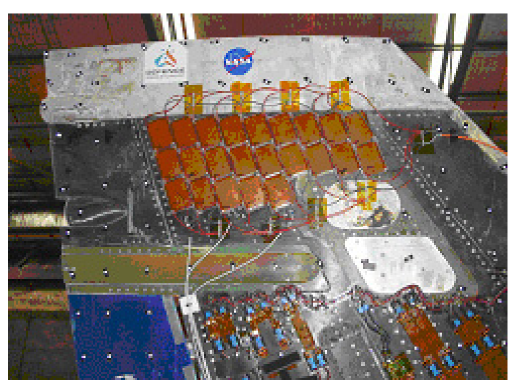

Figure 8. NASA LaRC MFC actuators installed on F/A-18 (ST01) in preparation for ground testing.

2.1 ACTUATORS

Based on a system analysis [21], it was shown that a 60-mil (1.5 mm) thick multi-layer directional actuator having properties of the LaRC Macro-Fiber Composite (MFC) actuator [22] performed best in suppressing vibration in the second mode of the fin. Prior to selection for the ground test, the MFC actuators were first tested as single layers embedded between fibreglass plies of the fin on 1/6-scale wind-tunnel model [23]. The actuator stack selected by the program consists of nine-layers of 7-mil (0.178 mm) thick ceramic fibres oriented 45 degrees to the longer edge of the actuator packaging, as shown in Figure 7. MFC actuator stacks were bonded to the vertical fin of the test article by NASA LaRC and DSTO personnel, and are shown in Figure 8.

2.2 AMPLIFIERS

Switch mode amplifiers (Figure 9) provide significantly higher power to piezoactuators at much better efficiency than similar sized linear drive amplifiers [24, 25]. The main reason for this is that switch mode amplifiers do not dissipate large amounts of power in the output device to drive the reactive loads, since these amplifiers have been designed to account for reactive loads from the piezoactuators. Therefore, switch mode amplifiers are smaller and have lower power requirement then a similarly rated linear amplifier.

The switch mode amplifiers developed for this program are nominally rated at 3.0kV$_{pp}$ at 2 amp. Two amplifiers were used in the test to drive banks of MFC actuators on each side of the tail. Isolation boxes (Figure 10) were placed on the output side of the amplifiers to protect them against electrical shock in the event of an actuator failure. This protocol was adopted based on experiences during the prior ground test. This amplifier system was tested during an initial testing program at NASA LaRC prior to shipment to Australia for this program [19, 25].

Figure 9. Switch mode amplifier

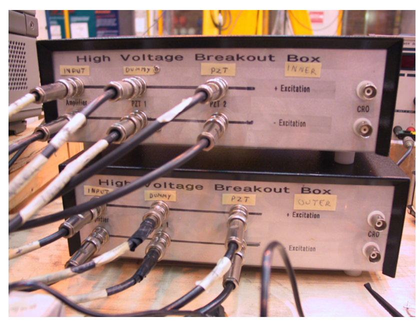

Figure 10. Amplifier isolation boxes

2.3 ACTIVE CONTROLS

This paper presents performances of control law designs based on the strategies explored by members of the multi-national team. All control laws were designed based on open-loop data from different sensors and simulated using appropriate system identification models, prior to implementing into the digital controller for testing with the actual hardware. In these simulations, closed-loop performance can be approximated and any potential sources of instabilities identified. This process mitigated risk to the test hardware, especially the amplifiers.

Once stability was verified through simulations up to maximum sensitivities, the control laws were transferred to the digital controller computer (right-hand side of Figure 11) and loaded into the controller signal box (Figure 12). The signals to and from the controller signal box were monitored using time history displays (computer on left-hand side of Figure 11), especially prior to closing the loop which would send the controller command signal to the test hardware.

The objective of each control law was to increase the damping of the resonating modes of the fin structure that were vibrated by the buffet turbulence. By increasing the damping, the magnitude of the loads as measured by the normal acceleration of the fin tip was automatically reduced. In terms of frequency response, these dynamics loads appear as peak responses at modal frequencies of the fin. For this aircraft, the peak responses of interest reside around 16 Hz (first bending mode) and around 48 Hz (first torsion mode).

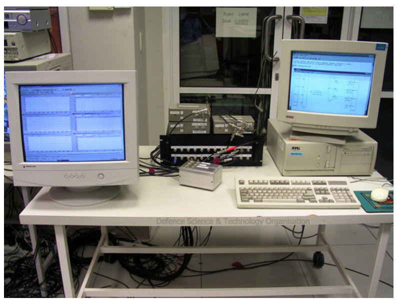

Figure 11. Digital controller hardware

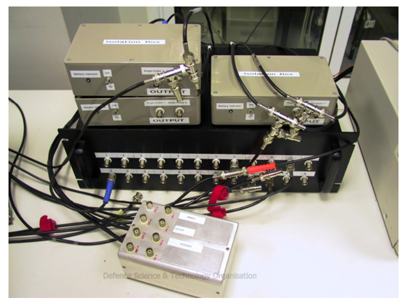

Figure 12. Controller signal box

2.4 LOADING CONDITIONS

Four types of buffet loads were applied to the fin during the closed loop test phase of the testing program, stemming from the following requirements: 1) maximum fin tip response condition (+ representative manoeuvre loads); 2) maximum fatigue damage at fin root condition (+ representative manoeuvre loads); 3) buffet sequence application (varying target buffet and manoeuvre load); and 4) broadband dynamic load application. These loads were derived from representative flight test data.

The target dynamic responses for these different load cases were then scaled to various levels and with different manoeuvre loads where appropriate to provide a number of options during the testing program. Each sequence lasted 30 seconds. In this program, it was intended to also apply the manoeuvre loads, as opposed to the initial program where only dynamic loads were applied; thus this program evaluated the performance of the control laws and the actuators under more realistic flight conditions. Time varying dynamic and manoeuvre loading sequences, per requirement 3, were also developed to evaluate fully the control laws. These sequences had the following characteristics: both manoeuvre and target dynamic loading varied; constant manoeuvre but varying dynamic loads; and varying manoeuvre but constant target dynamic loads.

The buffet loads were nominally applied by using two narrow bands: Band 1 frequency bandwidth of 10-20 Hz (1st Bending); and Band 2 frequency bandwidth of 34-52 Hz (1st Torsion). Therefore, in order to fully evaluate control laws, condition (4) was also applied. A broadband flat force spectrum was applied with a bandwidth of 10 – 60 Hz. This condition achieved a considerably lower maximum buffet load condition than that achieved by the two-narrowband bins. Hence in this case it was expected that the fin tip response would be considerably lower than that achieved by load conditions (1) through (3).

3.0 SYSTEM IDENTIFICATION

A precursor to designing any control law (for a system of any complexity) was to have a mathematical model of the system to be controlled [26]. A very common model is an LTI (linear time invariant) system. Even though the system to be controlled may be non-linear, which was the case with the F/A-18 empennage in the IFOSTP rig, an LTI description may still be adequate provided that the system was identified around the "normal" operating condition. This requires the system identification to take place with all controls working simultaneously as well as with the external disturbance (simulated buffet) being applied. LTI systems are best identified using sufficiently rich (in spectral content) and persistently exciting input signals. Typical inputs are band limited white noise or frequency sweeps. There are two controls in the test, one voltage to rotate the rudder the other to activate the piezoelectric ceramic actuators. Ideally maximum likelihood estimation procedures should be used so as to extract the best possible class of state space representation. However maximum likelihood estimation is a highly non-linear problem and as a result a local solution may be found rather than a global one. Using Singular Value Decomposition (SVD) applied either to frequency response data, impulse responses or to the original time series, this problem can be averted and a state space representation found. It is further proposed that these estimates are used as initial estimates in a maximum likelihood method. Commercially available software programs were used for computing the various state space and transfer function representations of the fin, actuators, and other system components needed before designing control laws.

4.0 RESULTING BUFFETING SUPPRESSION

One of the approaches used to control buffet load is active damping using simple control laws through the Micro Fiber Composite (MFC) actuator [23] and the rudder [20] feedback loops, as shown in Figure 6. This strategy was implemented during this test to control the first bending mode using the rudder and the first torsion mode using the piezoelectric actuators. In this test, the accelerometer near the trailing edge tip of the fin (Figure 6) was fed back to the control laws for both the rudder and the piezoactuators. This accelerometer is labeled 'KT16'. Using a frequency response method to design each SISO control law, an inverted notch with appropriate width (damping) was combined with band-pass filters placed at frequencies away from the mode of interest to minimize changes to the open-loop response. To minimize the control signal to an actuator stemming from measured accelerations of the other mode, a notch filter was placed in the control law for each actuator. For instance, a notch filter around 16 Hz was placed in the control law for the piezoactuators. As illustrated in Figure 13, over 70% reductions in peak acceleration of the first bending and first torsion modes were achieved during closed-loop control of the fin during buffet loads condition. Over the frequency band shown, a 24% reduction in rms acceleration was reached. However, additional improvements are possible through better filtering techniques, as indicated by the growth in response away from the two modes during closed-loop control ('BLA on').

Other more complex strategies using optimal control techniques were explored as well because of their potential to improve closed-loop performance [27]. When generating these optimal controls, the resulting control law may impact modes not targeted by the weighting matrix of the objective function. As in the case of the first strategy above, additional filtering was added to minimize the effect on the non-targeted modes. In some cases, sensors provide this filtering naturally by their placement on the node lines of the modes that are to be avoided. Also, through this strategy, there is the potential to employ both actuators (rudder and piezos) to control either or both modes simultaneously.

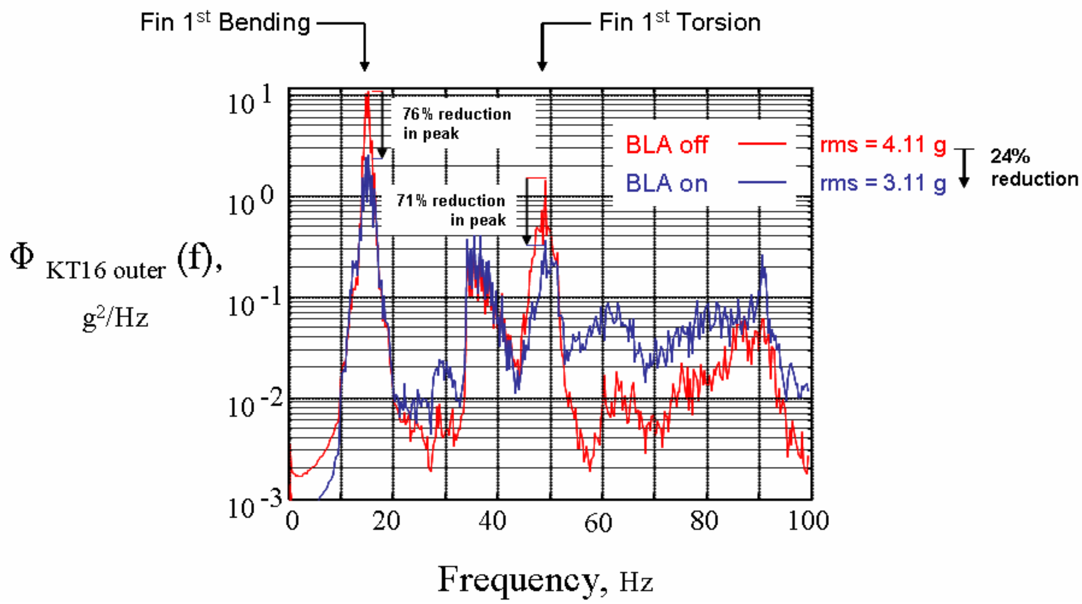

Figure 13. Performance results of "blended" single-input single-output control laws ("BLA on") for rudder (1st bending control) and piezoelectric actuators (1st torsion control) compared to no control ("BLA off")

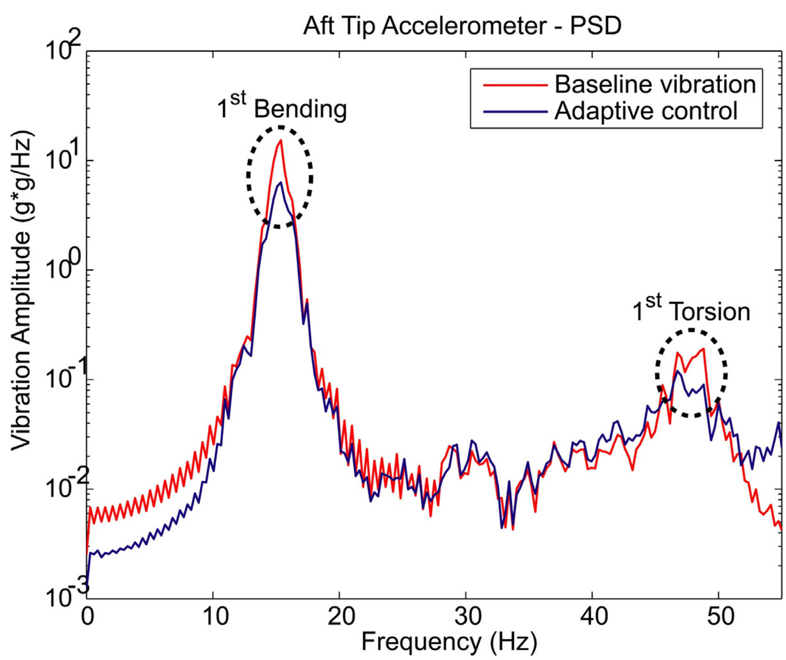

Figure 14. Performance results of multi-input multi-output LQG control laws ("Adaptive Control") for rudder (1st bending control) and piezoelectric actuators (1st torsion control) compared to no control ("Baseline Vibration")

With appropriate open-loop system models and the appropriate weighting matrices for objective functions, the state equations for an optimal control law can be generated using a LQG (Linear Quadratic Gaussian) regulator technique. This controller provided the best robustness to out of band disturbances and spill-over, as illustrated in Figure 14. However, its performance above 50 Hz was similar to the SISO controller performance shown in Figure 13. For the case of 75% of maximum buffet input load on the port fin, reductions of over 50% were achieved. For lower buffet load cases, even greater reductions were achieved (Table 1).

Table 1: Starboard fin vibration reduction for various input load cases using control law NRCC1

Starboard fin excitation (% of max)	Root bending mode reduction	Tip torsion mode reduction
12%	93%	95%
19%	66%	53%
29%	53%	55%
37%	48%	72%

5.0 CONCLUSIONS & RECOMMENDATIONS

The system has demonstrated performance sufficient to proceed with flight testing. The ground test validated many assumptions while putting many concerns to rest, specifically in the performance of the switch mode amplifiers. However, there are additional issues to address for improving system performance. First, if embedded within the structural plies of the fin, the piezoactuator would transfer its strain to the fin more efficiently. To embed the actuators would require new wiring designs. Based on the test, it is doubtful that the power electronics could be miniaturized sufficiently to be embedded with the actuators; hence, control computer and amplifiers will need to be accommodated elsewhere on the aircraft. Thus, an aircraft integration study and validation program would be required. Second, once embedded, the health of the actuators must be monitored through non-destructive evaluation methods. NASA has developed a system for this application that can be adapted for use during an aircraft integration study.

6.0 ACKNOWLEDGMENTS

The authors wish to dedicate their work under this TTCP activity to the memory of Dr. Thomas G. Ryall, formerly of DSTO, a fallen team member who was highly respected and is dearly missed. Dr. Ryall strived for optimal collaboration, many times neglecting his own needs for the benefit of this team. This work is also dedicated to the memory of Mr. Robert Fox, formerly of NASA Langley Research Center, whose contributions enabled the development of the piezoelectric actuators used in this test.

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