

BUFFET LOAD ALLEVIATION

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Abstract

High performance aircraft are, by their very nature, often required to undergo manoeuvres involving high angles of attack. Under these conditions unsteady vortices emanating from the wing and the fuselage will impinge on the twin fins (required for directional stability) causing excessive buffet loads, in some circumstances, to be applied to the aircraft. These loads result in oscillatory stresses, which may cause significant amounts of fatigue damage. Active control is a possible solution to this important problem. A full-scale test was carried out on an F/A-18 fuselage and fins using piezoceramic actuators to control the vibrations. Buffet loads were simulated using very powerful electromagnetic shakers. The first phase of this test was concerned with the open loop system identification whereas the second stage involved implementing linear time invariant control laws. This paper looks at some of the problems encountered as well as the corresponding solutions and some results. It is expected that flight trials of a similar control system to alleviate buffet will occur as early as 2001.

Keywords : Buffet Loads, Stress, Damping, Control, Smart Materials, Smart Structures, Piezoceramics, Fatigue

Introduction

Buffet loads cause large oscillatory stresses to be applied to the fins of modern military aircraft with a consequent loss of fatigue life. There are two important parameters that determine the stress distribution of an aircraft in flight. The first is AOA (Angle Of Attack) and the second is dynamic pressure (Q). The dynamic pressure *essentially* determines the overall magnitude whilst the AOA *essentially* determines

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the shape of the frequency response (ie how much fin bending is occurring compared to fin torsion and higher modes).

If the stresses could be reduced by 10% this would double the fatigue life and hence prevent premature ageing. As such, there is a strong incentive to devise ways of reducing stresses. This reduction may be accomplished by: 1) modifying the load-carrying structure within the tail, 2) reducing the buffet loads by altering the flow-field around the vertical tail, or 3) by reducing the buffeting response using smart materials and active control. The first two approaches have been the historical path. In particular, a special mention should be made of vortex control which has included blowing and sucking flow from various ports on the aircraft and at various rates, attaching different size and shape leading edge extensions (LEX) and attaching fences to these LEX. The historical approaches have suffered from the fact that they are not sufficiently robust over the range of operating conditions. What works well at one condition does not necessarily work well at another condition. The use of active controls has the advantage of giving more flexibility. One possibility for active control is to use the control surfaces. Ashley et al. [1] investigated an active BLA (Buffet Load Alleviation) system for various aircraft that employed the rudder as the primary actuator. Their analyses showed that if the rudder actuation frequency bandwidth could be increased to include that of the first structural mode, then the buffeting response could be reduced significantly through response feedback to an active rudder. Similar suggestions backed by experimental evidence have been made regarding the use of ailerons in the suppression of flutter [2]. The use of smart structures, however, gives a system that is independent from the flight control system and has the capability of controlling over a larger frequency band than through rudder control. There may of course be an argument for using both types of actuators at the cost of increased complexity. The certification process would also be expected to be more stringent in this dual approach.

Smart Materials

If a voltage is applied across a piezoelectric material, which is uniformly bonded to a structure then there is a change of area. Similarly, if the same material is subject to stress a voltage is generated. It follows that piezoceramic material can be used either as a transducer or as an actuator or as a transducer and an actuator. This effect was known as early as 1880 by Pierre & Jacques Curie although it took until 1950 before PZT (lead Zirconate Titanate) was commercially available. In the middle 1980's Crawley [3] at MIT proposed embedded piezoelectric ceramic composites for vibration control. Smart materials played a pivotal role in this work on buffet load alleviation giving a flexibility that was unavailable with more passive methods.

The Program

This problem of fatigue life reduction due to buffeting is of particular concern for those countries within The Technical Co-operation Program, (TTCP) that include the F/A-18 in their fleets. The TTCP is a program of technical collaboration and data exchange among five nations: Australia, Canada, New Zealand, the United Kingdom, and the United States. Of these participants, three countries, namely Australia, Canada, and the United States have initiated a collaborative research program aimed at a solution to this problem. The organisations involved include Airforce Research Laboratory (USA), National Research Council of Canada, NASA Langley and DSTO (Aeronautical & Maritime Research Laboratory) as well as two private organisations CSA and ACX.

Feasibility Study

In 1994, under the (US) Small Business Innovation Research (SBIR) Program ACX (Active Control eXperts-a spin - off from MIT) investigated the feasibility of using smart materials for the purposes of reducing the effects of buffet loads. The imposed constraints were that the mass of piezoceramics added to the fin (see Fig (2)) must be 25lbs or less per fin, and the maximum strain per piezo-patch should be 400 micro-strain or less. The control objectives were to reduce the strains in a “global sense” by an order of 50% subject to the aforementioned constraints. The study [4] also examined an optimal layout for the distribution of the piezoceramic material based upon the (dilatational) strain energy density. Since control of both the bending and torsional modes was required, the piezoceramics were formed into two groups each being driven by independent voltages. The curve separating in space these two groups is given by the locus of the zero crossing of the sum of the principal stresses (or strains) in the second (torsional) mode. This corresponds to a line of zero (dilatational) strain energy density. Of course, either group of actuators was able to excite either mode. Mirror image actuators were put on the other side of the fin but were locked into 180° phase change so that while one surface was contracting the other surface was expanding, as in local bending. The study was based on finite element analysis, as well as NASA wind-tunnel results and Canadian flight trial data. The results of this study plus the work done on sub-scale models [5,6] were sufficiently encouraging to proceed to the next phases.

The Test System

A unique full-scale fatigue test system has been developed at the Melbourne based Aeronautical & Maritime Research laboratory (AMRL) which simulates the loads experienced by an F/A-18 in flight. High-powered high displacement electromagnetic shakers are used to apply the dynamic buffet loads (see Fig (1)). The test article used in the BLA work is illustrated in Fig (2).

Open loop system identification

Before any control law can be designed it is necessary to have information about the system to be controlled. In general this takes the form of a mathematical model which describes the connections between inputs and outputs. Numerous texts as well as journal articles have examined the problem of system identification [5]. For hardware reasons the transfer functions were determined in the frequency domain. The sensors that were available included accelerometers (fore and aft at the tip of the fin) and strain gauges (fore and aft at the root). The hardware configurations were such that only a two-input and two-output system could be used at any one time. Energy was supplied to the fin (simulated buffet loads) by the shaker in two frequency bands 10-20 Hz and 34-52 Hz. These ranges cover the significant frequency responses which are centred near 15 Hz (bending mode) and 45 Hz (torsion mode). White noise sequences were used in these bands with the relative scales depending on AOA and Q. The system had three inputs and a total of 22 outputs (accelerometers and strain gauges). Initial estimates of transfer functions had to be discounted due to significant non-linearity introduced by the shaker system. If a system is non-linear then it must be linearised about the normal operating condition. When it is at rest the shaker has a great deal of friction associated with it. As a result, the fin at the point of attachment of the shaker has an “artificial” node for all modes at this point. At all times it was necessary to have all three inputs activating the system to overcome this non-linear behaviour. Although the three inputs consist of statistically independent noise sequences, treating them in isolation would require a large

number of ensemble averages and hence long time records, especially at flight conditions corresponding to severe buffet loads. Treating them together provided an estimate that had the smallest possible variance at the cost of more calculations. From the frequency responses it was then possible to obtain state space models using either non-linear least squares or maximum likelihood estimation. (see appendix). State space models were obtained that were valid from 0-100 Hz although frequency responses were obtained for the actuators that were valid from 0-1 KHz. (This latter information was used to check stability of the closed loop). Typical models that were found involved 18 states with two inputs and two outputs.

Closed Loop Control

The real objective in this work was to increase the damping in the dominant structural modes. Increasing the “stiffness” of the structure was likely to increase the frequencies and if the external excitation was sufficiently broad-band then the overall response will not be diminished by this technique. Similarly trying to decrease the stress at the critical open loop position might very well make it worse in another location. A number of different design methodologies were tried including linear quadratic methods [8] and frequency weighted linear quadratic methods, pole assignment and

SISO (Single Input Single Output) classical design approach. The sensors used included a mixture of accelerometers and strain gauges, as was mentioned previously, the control law was limited to two inputs and two outputs. A maximum of 28 states was allowed for the controller, to guarantee that the calculations could be completed in the required time (sampling rate 5 KHz). The high sampling rate was required since the DSP (Digital Signal Processing board) automatically introduced 5.5 sample delays irrespective of the sampling rate used, this delay is important especially with respect to the size of the residues of the transfer functions. The effect is more pronounced with the higher frequency modes as to be expected.

Results

The closed loop trials were carried out at a number of different flight conditions. At flight condition 1 (FC1) the critical strain was reduced by 51%, while at flight condition 3 (FC3) the reduction was 15%. Fig 3 shows a comparison of strain density as a function of frequency between the open loop and closed loop configurations at FC1. At flight condition 6 the stresses were reduced by a modest 2% this condition is almost the most severe buffet situation possible it is also the condition at which the aircraft spends the least amount of time. Similar reductions occurred in the various accelerometer readings. From these results it is estimated, taking into account usage rates in the various AOA/Q regimes, that if BLA were installed on an F/A-18, the increase in life would be approximately 70% or in other words, 4000 hours could be added to the life of the tail. It should be emphasised that the shaker as well as adding non-linearities also increased the damping especially in the fundamental mode (bending). The bending mode was found to have a damping of about 9%, although normally structural modes have a damping of approximately 1-2%. With aerodynamic damping (as seen in flight) this might increase to around 4-5%. As a consequence the damping of this mode was about twice that of what it should have been. As a result of this increase in damping, it is expected that in practise results will improve by a factor of two or more in the real situation.

Future Directions

Flight trials are planned either in Canada or the USA by the year 2001. In the interim there is a need to reduce the size and weight of the amplifiers that drive the piezoceramics. In the program, 16 large linear audio amplifiers were used. Recent developments in switch mode amplifiers show that both weight and volume can be reduced by a factor of twenty or more. The present piezoceramics apply a stress to the surface of the body due to a voltage applied across the thickness. In other words, the electric field is at right angles to the desired direction(s) of stress and as a result the action is a result of Poisson's effect. New research and development with interdigitated electrode patterns which allows use of the d_{33} term (d is the piezoelectric constant and is a third order tensor) means that the same voltage can deliver between 2 and 3 times the effective stress. That is, there is an increase of efficiency of more than 200%. DSP boards are also constantly being improved allowing for more calculations to be done per unit time. The problem of having a time delay which is a function of the sampling rate is no longer an issue (with modern DSP's) which means a more appropriate rate of 1 KHz could be used. The work to date has demonstrated that piezoceramics can be used successfully in full-scale structures to reduce vibrations of the order of inches. Previous work has been restricted to relatively small vibrations carried out in laboratories on small structures that in the main have been acoustically excited.

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Appendix: System Identification

Let I_1, I_2, I_3 be the fourier transforms of the three inputs, the first two being the piezoceramic actuator inputs whilst the last is the reference signal for the simulated buffet. Let T_1, T_2, T_3 be the transfer functions between any transducer and the three actuators corresponding to these inputs then the “best estimates” we have of T_1, T_2, T_3 are given by the normal equations, viz

$$\begin{pmatrix} 1/n \sum_1^n I_1 I_1^* & 1/n \sum_1^n I_2 I_1^* & 1/n \sum_1^n I_3 I_1^* \\ 1/n \sum_1^n I_1 I_2^* & 1/n \sum_1^n I_2 I_2^* & 1/n \sum_1^n I_3 I_2^* \\ 1/n \sum_1^n I_1 I_3^* & 1/n \sum_1^n I_2 I_3^* & 1/n \sum_1^n I_3 I_3^* \end{pmatrix} \begin{pmatrix} T_1 \\ T_2 \\ T_3 \end{pmatrix} = \begin{pmatrix} 1/n \sum_1^n O_1 I_1^* \\ 1/n \sum_1^n O_2 I_2^* \\ 1/n \sum_1^n O_3 I_3^* \end{pmatrix}$$

In the limit as $n \rightarrow \infty$ the matrix becomes diagonal however for finite n the above equation is more accurate and has smaller variance. Given T_1, T_2 it is required to obtain a state space representation. T_3 characterises the external disturbance and is not normally available. If the true T_1, T_2 are represented by $\sum_j (A_j s + B_j)(s^2 + \alpha_j s + \beta_j)^{-1}$ and $\sum_j (C_j s + D_j)(s^2 + \alpha_j s + \beta_j)^{-1}$ (where

s is the Laplace variable) respectively then a modified least squares Newton-Rhapson method can be used to guarantee convergence to at least a local minimum . Initial estimates are obtained in the following manner; T_1, T_2 are initially represented as $N_1/D, N_2/D$ where N_1, N_2, D represent high order polynomials in s . The following modified least squares problem which is linear in the parameters is solved $\sum \|N_1 - T_1 D\|^2 + \|N_2 - T_2 D\|^2$ where the summation is over the frequency domain and $\|Z\|$ is the normal Euclidean norm for a complex variable Z . Using globally convergent polynomial solvers, initial estimates can be obtained for α_j, β_j , initial estimates for A_j, B, C_j, D_j can then be obtained by solving the nonlinear least squares equation with fixed α_j, β_j . This then reverts to a linear problem. This initial estimate whilst not unbiased or minimum variance is certainly consistent and will be “close” enough for convergence for a sufficiently large enough value of n . The extension of the method to more than one output is obvious. High order systems can be treated stably in this manner.

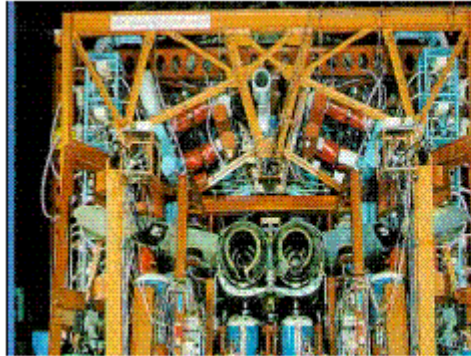


Fig 1
AMRL's rig used to apply both manoeuvre loads and dynamic buffet loads.

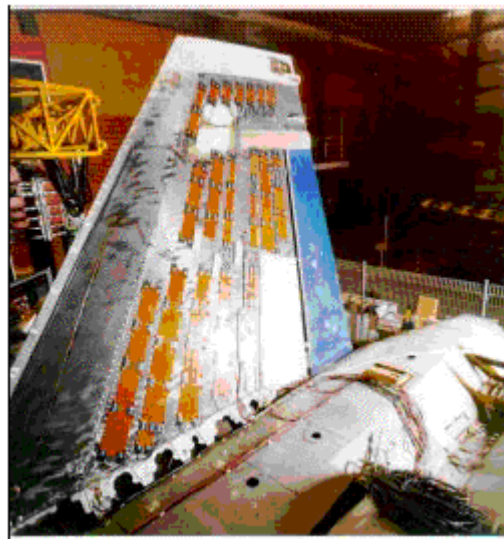


Fig 2
Piezoceramic actuators on one fin of an F/A-18 test article

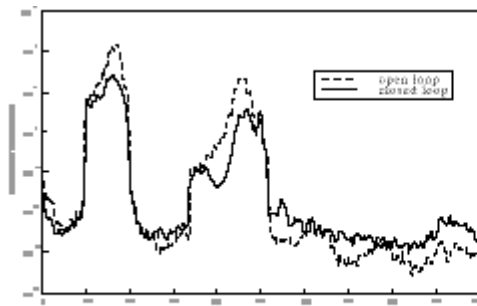


Fig 3
Comparisons of strain density between open and closed loops at the critical location for flight condition 1.