ACTIVE VIBRATION SUPRESSION CONCEPTS FOR BUFFET EXCITED VERTICAL TAILS

Johannes Schweiger, John Simpson, Otto Sensburg

Daimler-Benz Aerospace AG, Military Aircraft
P.O. Box 801160, D-81663 München, Germany

Abstract

A brief overview is given on the nature of the aeroelastic phenomenon known as fin buffeting which restricts the performance of fighter aircraft. Several concepts are described and discussed, how the impacts from these forced vibrations on the structure of vertical tails can be alleviated by active means.
One group of concepts for the active suppression of these vibrations makes use of aerodynamic forces, generated by devices attached to the fin. Promising new concepts emerged from the development of new kinds of material in recent years. These active materials can be integrated into the structure to control vibrations by changing their stiffness and damping properties. This is achieved by electrical energy.
Most of these concepts have already been proposed by other authors. Several theoretical and few experimental studies have been conducted to demonstrate the feasibility and effectiveness of these concepts, but a successful demonstration in flight is still missing for all of them.
This paper gives a summary of these concepts, describes the status of development activities, and tries to evaluate their effectiveness.
Because active structural systems could control other vibration problems in aviation and, more general, in all technical areas, where vibrations are encountered, these aspects will be discussed in more detail.

Introduction

According to classical books on aeroelasticity (1) (2), buffeting summarizes a group of dynamic response problems in aircraft design. These are in general vibrations of the aircraft or individual components, being excited by turbulences or flow discontinuities, generated by the aircraft itself. These irregular aerodynamic loads can excite the surface where they originate, as on a wing, or a surface in the wake of that flow, such as a tail surface.
Compared to the other aeroelastic phenomena like flutter, structural divergence, or control surface reversal which already showed up very early in the history of aviation, buffet or buffeting was not considered a major problem until the sixties. The expression buffeting was used for the first time by British scientists, who investigated the accident of a Junkers transport aircraft in England in 1930 (2) (3). In this incident a strong gust had caused an increase in angle of attack, resulting in the destruction of wing struts from buffeting. Also described in ref. (3) is one of the first incidents related to tail buffeting, in which a McDonnell aircraft was involved in 1933.
As described by Ashley (4), buffeting began to stand out as an operational issue during World War II, when fighters became capable of sustaining local transonic flow conditions on their upper wing surfaces. The shock induced excitations are causing limitations of the envelope at critical Mach number and angle of attack combinations.
Fin buffeting became a more serious problem in the late sixties, when advanced aerodynamic designs for modern fighters made it possible to increase their agility by operating at high angles of attack (AOA). Fig. 1 depicts this trend. These designs use highly swept wing leading edges, especially in the inboard section, in many cases combined with so called leading edge extensions (LEX), strakes, or chines. These devices generate high energy vortices, that remain stable up to high angles of attack, thus contributing additional lift. These vortices however create a highly turbulent environment in the vicinity of the vertical tail. It is often believed that only twin tail configurations like F-14, F-15, and F-18 are suffering from these conditions because a single tail in the symmetry plane will not be hit by the turbulent flow. But the degree of turbulence, especially in the combination with sideslip angles, becomes so high at high angles of attack, especially when vortex bursting occurs ahead of the tail,

that practically all single tail fighters are experiencing the same problems as twin tail configurations. This can also be explained by the fact that a single fin needs a larger area, although the aerodynamic environment may be less severe. Due to their larger mass and higher flexibility they will then endure dynamic response levels of the same magnitude.

Excellent overviews and more details about fin buffeting are given in the already quoted references (3) and (4). Fig. 2 shows typical acceleration levels at fin tips and the expected improvement with respect to manoeuvrability or load reduction for active vibration control concepts.

In 1995, a research programme was launched at DASA to evaluate the feasibility and effectiveness of different active vibration suppression concepts. This programme is a joint venture with the German aerospace research establishment DLR and Daimler-Benz Research Laboratories.

Aerodynamic Aspects of Fin Buffeting

Although the flow in the plane of vertical tails is highly turbulent at high angles of attack, its nature can be characterized by several parameters. In general, the leading edge vortex cores experience a rapid expansion ("vortex burst") in front of the vertical tail, the tangential flow velocity increases with the diameter, and the flow shows large fluctuations. The turbulent flow contains a narrow band frequency peak, which increases with angle of attack.

This peak can be described by the dimensionless reduced frequency ("Strouhal number")

$$k = \frac{f * c * \sin\alpha}{V_\infty}$$

with vortex frequency f, mean aerodynamic chord c, angle of attack α and free-stream velocity V_∞. The frequency of the peak averaged pressure on all fighter configurations decreases with angle of attack, as depicted in Fig. 3 from (3). This reference also depicts the variation with airspeed, Fig. 4, and the normalised dimensionless pressure, Fig. 5. This peak occurs at all known single and twin fin configurations at reduced frequencies between 0.5 and 0.7. As shown by other authors like in (4) and (6), Reynolds number and Mach number are of no primary importance for fin buffeting. This allows simple model scaling. Mach number effects are unimportant, because the high angles of attack manoeuvres are flown at low to moderate Mach numbers.

On single fin configurations, the side slip angle is an additional important parameter: Fig. 6 from (6) show the different flow conditions with and without side slip. In this experimental effort the time-dependent flow velocities were measured in the plane of the vertical tail by hot wire anemometers, Fig. 7, and the source of vortex generation was investigated by laser light sheet flow visualization.

To analytically predict the buffeting behaviour for a new configuration, CFD methods are not yet capable to describe the complex flow conditions behind the vortex burst location. All known prediction methods are based on wind tunnel data.

A unique kind of fin buffeting investigation was performed at NASA-Ames on a full scale F-18 (5). In this test, both fins were instrumented with pressure transducers and accelerometers. Fig. 8 shows the aircraft installation in the wind tunnel. A 6x6 pressure transducer grid was used on the right tail by Wright Lab engineers, the left tail was instrumented by NASA engineers, using a 8x6 grid. Fig. 9 is a typical plot of nondimensional differential pressure PSD with a peak at $k = 0.6$ for 32° AOA.

A new measurement technique for unsteady pressures was for the first time used at the authors' company in 1995 for fin buffeting investigations. Thin-layer piezoelectric pressure transducers, developed at the Technical University of Berlin (9), were used. They can easily be applied and removed on the external surface of the model. Data reduction is still ongoing, but the results are showing a great potential for the application on all kinds of existing models without the need of costly modifications.

Structural Aspects of Fin Buffeting

Based on the aerodynamic characteristics, a first recommendation for structural design of vertical tails could be: "Avoid eigenmodes in the frequency range of the peak aerodynamic excitation". Unfortunately, the peak is rather broad and the first bending mode frequency is usually located in this range. To shift it to a higher frequency will cost a lot of weight, and to shift it to a lower frequency is not compatible with other design stiffness requirements like flutter stability or static aeroelastic effectiveness. In addition to this, structural eigenmodes are also experiencing heavy excitation levels outside of the peak frequency range because of the broad band turbulent flow at high angles of attack.

It is well known from single and twin fin configurations that considerable efforts are required to reinforce the fin structure in critical areas in order to obtain acceptable fatigue life or expand the flight envelope to higher angles of attack for better manoeuvrability.

The fin tip region is a popular place for the installation of all kinds of equipment like antennas, radar warning sensors, or transmitters. Because of the extreme buffeting acceleration levels, this position is causing unfavourable conditions for the design of the equipment and its attachment to the structure with respect to vibration levels and the performance of the equipment. On top of this, the mass of the installed equipment is aggravating this situation.

Because passive means like reinforcing the structure or modification of the aerodynamic shape where the excitation forces originate show only limited improvements, active concepts are promising a great potential for the enhancement of fighter manoeuvrability and for the reduction of life cycle costs.

Active Aerodynamic Buffet Alleviation Concepts

This type of systems can be divided into two major groups: concepts to reduce the strength of the buffet excitation source, and concepts to counteract the structural response by aerodynamic means.

Several concepts have already been proposed in the past for the first group, like air blowing along the wing leading edge, to modulate the vortices. In a recent research programme (10) actuated forebody strakes hinged along the fuselage, were successfully used on F/A-18 for yaw control and improved manoeuvrability. Either these surfaces or parts of the leading edge extension could also be used to alleviate the buffet loads on the tail.

For the second group of active aerodynamic concepts several theoretical investigations were performed in the past to use aerodynamic surfaces attached to the vertical tail for the alleviation of the buffet response. In the study by Ashley et al. (4), the rudder was successfully applied on the F-18. Using a realistic gain factor for the rudder deflection, the predicted fatigue life could be improved by factors between 7 and 25, depending on the chosen stress concentration factor. Fig. 10 shows the open and closed loop power spectral density for the fin root bending moment with a gain factor to cause 3.2° RMS rudder deflection, which gives a 33% reduction in RMS bending moment.

The same approach was also applied on the F-15 vertical tail. But in this case the rudder was less successful as an aerodynamic effector for buffeting reduction. A small vane at the fin tips, Fig. 11, showed more promising results. In this case, the tip acceleration was used to express the effectiveness. Fig. 12 shows the input spectrum for the unsteady pressure, the open and closed loop acceleration PSD, and the vane activity for a gain factor of 0.1 (3.56° RMS angle). The inserted table gives the RMS levels for different gain factors.

The major uncertain parameter in this study is the aerodynamic effectiveness of the control surfaces. It is well known that control forces and moments are overestimated by theoretical methods like doublet-lattice due to the kink at the hinge line, gaps, and boundary layer effects. In this study reduction factors for the rudder yawing moment with increasing angle of attack were based on High Alpha Research Vehicle (HARV) flight test data. This factor mainly takes into account the reduced dynamic pressure at the tail because it is located in the shade of wing and fuselage with increasing angle of attack. Using a theoretical model like the one depicted in Fig. 13 for the F-18 study, one should consider an additional effect at high angles of attack. The effective aspect ratio of the rudder is reduced by the sweep angle effect due to AOA. Therefore a modified idealisation with spanwise divisions parallel to the free flow like in Fig. 14 should be considered.

An additional reduction for the unsteady rudder effectiveness may be necessary because of the highly turbulent buffet flow conditions.

Based on the U.S. Air Force Data Exchange Agreement with Germany, two of the authors were invited in 1995 to participate in a NASA/Air Force wind tunnel test programme for active fin buffet load alleviation concepts at NASA-Langley. The programme's name ACROBAT stands for "Actively Controlled Response of Buffet Affected Tails".

Within this programme, several concepts were tested on a 16% scale rigid wind tunnel model of the F-18. For this purpose, rigid fins with pressure transducers were used to measure the buffet excitation forces, and several dynamically scaled flexible fins were manufactured and instrumented for these concepts:

- active rudder, driven by a hydraulic actuator
- rotating, slotted cylinders, mounted in various position near the fin tip, acting like a vane
- piezo ceramic actuators, distributed over the structure.

The last concept will be discussed in the next chapter. More facts about this programme are given in reference (7), the principle of the slotted cylinders, originally invented by Wilmer H. Reed III as flutter test exciters is described in more detail in reference (8). Fig. 15 shows the different configurations for aerodynamic control concepts.

The authors' preliminary conclusions from these tests are:

- the rudder can be used as an efficient control device, but its effectiveness is reduced with increasing angle of attack
- the unsteady forces generated by the slotted cylinder (or tip vanes) seem to be too small to

create sufficient aerodynamic damping

- the loss of effectiveness with increasing angle of attack seems to be larger than predicted in the above mentioned theoretical investigation [4].

Internal Structural Control of Buffet Vibrations

General Remarks

The concepts to be presented mainly highlight new materials and topology of their implementation. The task at hand is to clip off peak levels of buffet vibration. The utmost conceivable strain a system would have to bear, at least passively, is many hundreds of μ–strains but at least much less than say present on a helicopter rotor and other high aspect structures. The system must be safe for temperatures ranging from -40°C, 100°C, humidity, lightning, show maintainability, be easy to inspect, and be "clearable" within the main frame-A/C system requirements.

As indicated above, the information link between upstream source and induced vibration is literally burst in buffeting. The relationship between A/C movement e.g. from an inertia platform and interwoven load on the tail is poor. This motivates Random analysis (statistical-structural) and test methods. A measurement, in-flight, directly at the fin structure would e.g. identify a hovering harmonic load component from port and starboard vortices pounding on the lightly damped structure. This is only one part of the broad banded to peaked frequency load content.

The encountered scope of load involvement and identification process is a trying test bed for smart material abilities as actuator, sensor and even localised memory. Other use of these structural elements would mainly address

- elastic mode control in high load environment
- panel flutter (local bucking)
- dissipation, reflection and cordoning off of vibration propagation of acoustic frequency range vibrations or transient loading
- adjustment of system characteristics e.g. eigenfrequencies

Without being biased to one concept, an example of a piezoceramic application is picked out which helped to spark current activities. In this piezoelectric crystal assembly fixed to a rotating system, Fig. 16, Crawley [11] used the piezo as transducer, exciter and as means to vary the 375 Hz-blade bending frequency by 6Hz (tightening the piezo to blade fixture through a bolt). In many respects it reflects a typical "interface" or root control candidate. It was a well integrated versatile component (used on 23 blades of the MIT aeroelastic rotor) sustaining for example a 9000rpm (150 Hz) load environment.

Current Theoretical and Experimental Investigations

One of the most thorough theoretical investigations to date was done by Lazarus, Saarmaa and Agnes [13]. They used integrated piezo actuators to damp the vibrations of a F-18 fin structural analysis model. The incurred mass penalty was 8% but they showed a 50% decrease in strain RMS values.

The first relevant fin buffeting experiment using piezo actuators is documented in [14]. Here, the structural response of a Windtunnel 1:20 scaled model, dynamically resembling the F-18, was reduced by 65%. This would imply an enormous fatigue life benefit. Typically, the piezos were bonded on a beam which in turn supported the surrounding aerodynamic shell.

In the already mentioned NASA/U.S. Air Force programme ACROBAT [7], distributed piezo actuators were applied onto the structure of one fin, represented by an aluminium plate. The supergroups of piezos were distributed over the surface as shown in Fig. 17.

Within the above mentioned DASA programme the following concepts, depicted schematically in Fig. 18, will be investigated:

- structurally integrated piezo actuators
- adaptive interface i.e. an active component concentrated in the fin-fuselage joint (root control)
- active vibration suppression using the rudder
- active servo rudder or slotted cylinder, creating unsteady aerodynamic forces, explained above.
- adaptive mass damper system.

Structurally Integrated Piezo Actuators

They are systems which can be bonded onto an arbitrary surface or even embedded into the structural surface. A perpendicularly applied voltage, upholding a charge just as a capacitance, induces strain in the piezo which is transferred in plane to the structural shell.

Crawley published many papers, which serve at a basic theoretical background for many researches. In [12] a one-dimensional "uniform strain" model (known also to sandwich structure design) can be found. Based on this theory, Fig. 19, is obtained for a typical fin shell structure with a Scotch weld bond of a surface attached piezo. It frames the normalised strain distribution along this piezo/structure interface. The boundary conditions at the length wise ends (the bonded length is used to normalise the X-coordinate with the local axis placed centrally) of the actuator are that the piezo has full strain whereas there is still no strain developed in the substructure. Typically, the piezo and substructure strain level join up quickly to a "perfect bond" or common strain level because the bond is very effective in terms of Γ (shear effectiveness). If the psi parameter (ratio of substructure stiffness to piezo stiffness) is lower, the strain accumulated at the fin skin surface would be greater than the depicted 33% of initially induced piezo strain. $\alpha=2$ means that a piezo is uniformly activated above and below the skin. Unfortunately, the mean strain, or picking out the neutral axis, would only receive a fraction of this, especially if only the inner or outer skin side can be piezo patched. For this reason, practical experiments have often seen very thick piezo layering, pointing to the main clinch in this technology: strain capability.

Theoretical modelling design approaches are ranging from element system approach (Bernoulli bending, directional actuation on orthotropic media etc. (15), (16) to full FEM field equation formats including closed electro-mechanical coupling (21).

Multilayering techniques have been developed with keeping voltage amplitudes down, which may be decisive for A/C systems. The compound piezo systems do tolerate noticeable passive strain, but in actuation and contemplating active cyclic loads they depolarise at much lower strain, a few hundred micro strain. The application of the first model, although neglecting transverse strain effects etc., gives ample evidence to relegate contemporary embedded piezos from implementation in a buffeted fin. Table 1 (16) serves as a state of art material guide. Data in table 1 imply that polyvinylidene fluoride type piezos (PVDF) are suited to sensor tasks as used in (9) and lead zirconate titanate type piezos (PZT) to actuation. There is understandably a lot of scepticism among chief designers when the word "crystal" and "sintered" is mentioned: brittleness and poor ductility (low K_{IC} values) (17) (18), challenges for inspection standards such as ultrasonic microphoning etc.

PZTs prefer to contract and provide greater strain parallel to the electric field. From this stacked PZTs, with their electrodes sealed to a clamped pillar, have evolved; so-called rod actuators. Others, of one layer, are clamped concentrically, contracting to bend away normally: benders (with relatively heavy clamps because piezos crack easily at curvature tensed joints). The latter system is the main constituent of the next concept discussed.

Adaptive Interface (Root Control)

Placed at the fin-fuselage joint, the actuators would have to confront the maximum inertia and elastic load. An inkling of what maybe feasible has already been shown in Fig. 16. Although these systems can exploit a greater blocked force in dynamic offset operation one cannot envisage them handling the main fin load path. Parallel load path alignment is also a risky task. They may perform well though as sensor or backup exciter safely integrated between tail beam and flexible fin base bulkhead/ or fin leading edge regions (safe from erosion, mechanical dismantling i.e. no gluing, relatively harmless mass position penalty and other advantages). Structural analysis modelling considerations are easier and more consistent with basic available algorithms: linearly dimensioned, single point boundary conditions. Importantly, they can be grouped together with amplifier components. This is possibly an advantage over surface elements which as a large area or super group require near short-circuit amplifier operation.

Passive or Active Mass Damper Systems

Passive mass damper systems will not work for fin buffeting, because the excitation spectrum contains a multitude of narrow and wide band frequency components which in addition are changing with flight conditions.

Even if the system could manage to control a certain inherent dominant harmonic load, it would create severe conditions for other aspects like flutter. It would also require a minimum elongation for the mass, which is impossible within the contours of the fin. An active single-degree-of freedom damper can only be used for special applications because there is always a fixed mass damper quantity associated with an optimal control of relative basement motion feed back fitted to a certain vibration excitation. The system would suffer from buzz and it would carry over transient loads from one manoeuvre to another. This deficit was already mentioned in other studies (19) (20).

But these systems are versatile in vibration control for locally suspended equipment.

Conclusions

The survey on fin buffeting revealed that all modern single and twin fin fighter configurations are suffering from this severe dynamic response problem.

Extended experimental research programmes in the past decade helped to understand the complex aerodynamic flow conditions. This knowledge for experiments is still required for predictions because CFD methods are not yet capable to correctly describe the turbulent flow created by several burst vortices.

Several concepts were investigated how the impacts from fin buffeting on the performance and structural integrity of fighter airplanes can be alleviated by active means.

To use the rudder as a control device offers one great advantage: it can be done at almost no extra cost, because it is already there. Unfortunately its effectiveness is reduced with increasing angle of attack. That means, the effectiveness has a minimum in the AOA range where it is needed. The performance of the rudder actuator limits the application to low frequent modes, and the motion of rudder and actuator will introduce new loads into the structure. The introduction of the control system for this concept into an existing digital flight control system will further increase the already very complex architecture of such a system.

Additional aerodynamic devices like vanes seem to be even more limited in their performance because of their relatively small size. They require extra efforts for their integration and their additional mass first deteriorates the buffeting conditions before they can cure them.

The effectiveness of active structural concepts, especially those based on piezoceramic actuators, distributed over the structure, was already demonstrated by theoretical studies and small scale experiments. Although not all aspects of their integration into a real aircraft - like compatibility with environmental conditions, EMC, energy supply, robustness - have yet been demonstrated, they offer the following advantages:

- small mass increment, distributed over the structure
- almost unlimited capacity in response time and frequency range
- they can be integrated into an existing structure
- their effectiveness is independent from the aerodynamic environment
- no moving parts.

These promising new concepts will need some further research to gain more experience and reliability, improve the analytical methods to describe their physical properties, and optimize their integration into the structure as well as their control system.

Acknowledgement

The authors express their appreciation to Ed Pendleton (Wright Laboratory) for arranging the participation in the ACROBAT test programme, and to Thomas E. Noll and his whole staff at the NASA Langley Research Center for their hospitality during the test. Special thanks to Robert Moses, the lead engineer, for many fruitful discussions, and for the way how he succeeded to perform the test programme under sometimes difficult circumstances.

References

(1) Bisplinghoff, R.L.; Ashley, H.; Halfmann, R.L.: Aeroelasticity, Addison WesleyPublishing Co., Reading, MA, 1955.

(2) Försching, H.W.: Grundlagen der Aeroelastik, Springer Verlag, Berlin, Heidelberg, New York, 1974

(3) Ferman, M.A.; Patel, S.R.; Zimmermann, N.H.; Gerstenkorn, G.: A Unified Approach to Buffet Response of Fighter Aircraft Empennage. AGARD C.P. No. 483, Sorrento, Italy, 1990.

(4) Ashley, H.; Rock, S.M.; Digumarthi, R.;Chaney, K.; Eggers, A.J.: Active Control for Fin Buffet Alleviation. WL-TR-93-3099, Flight Dynamics Directorate, Wright Laboratory, Wright Patterson AFB, OH., USA, 1994

(5) Pettit, C.; Banford, M.; Brown, D.; Pendleton, E.: Pressure Measurements on a F/A-18 Twin Vertical Tail in Buffeting Flow. Volume I - Wind Tunnel Test Summary. WL-TM-94-3039. Wright Patterson AFB, OH, 1994.

(6) Breitsamter, Ch.; Laschka, B.: Turbulent Flowfield Structure Associated to Fin Buffeting Around a Vortex-Dominated Aircraft Configuration at Sideslip. ICAS-CP 94-4.3.1, Anaheim, CA; 1994.

(7) Pinkerton, J.L.; McGowan, A.-M.R.; Moses, R.W.; Scott, R.C.; Heeg, J.: Controlled Aeroelastic Response and Airfoil Shaping Using Adaptive Materials and Integrated Systems. SPIE Vol. 2717-10, 1996.

(8) Bak, D.J.: Rotating Cylinder Excites In-Flight Vibration Modes. Design News, March 1989.

(9) Nitsche, W.; Swoboda, M.; Miro P.: Shock Detection by means of Piezofoils. ZFW No. 15, pp. 223, 1991.

(10) F/A-18 HARV Exploits Forebody Control. Aviation Week & Space Technology, 20th Nov. 1995

(11) Crawley, E. F.: In-Plane Inertial Coupling in Tuned and Severely Mistuned Bladed Disks ASME Jornal of Engineering for Power, Vol 105,

July 1983, pp. 585-590.

(12) Crawley, E. F.; Javier de Luis:
Use of Piezoelectric Actuators as Elements of Intelligent Structures. AIAA Journal 25 No. 10, 1373-1385.

(13) Lazarus, K. B.; Saarmaa, E.; Agnes, G. S:
An Active Smart Material System for Buffet Load Alleviation. Society of Photo-Optical Instrumentation Engineers, Vol. 22447/179, Bellingham, WA, 1995.

(14) Hauch, R. M.; Jacobs, J. H.; Ravindra, K.; Dima, C.: Reduction of Vertical Tail Buffet Response Using Active Control. AIAA-CP-95-1080; Washington, 1995.

(15) Park, C.; Walz, C.; Chopra, I.:
Bending and Torsion models of Beams with Induced-Strain Actuators.
Smart Mater. Struct. 5 (1996) 98-113,
IOP Publishing Ltd. UK.

(16) Barrett, R.:
Aeroservoelastic DAP Missile Fin Development.
Smart Mater. Struct. 2 (1993) 55-65,
IOP Publishing Ltd. UK.

(17) Schmidt, E.:
Kristallplastizität
Springerverlag, 1935.

(18) Bunk, W. et al.:
Keramische Komponenten für Fahrzeug-Gasturbinen III
Statusseminar BMFT, Springer Verlag, Febr. 1984.

(19) Nishimura, I. et al.:
Active tuned mass damper.
Smart Mater. Struct. 1(1992) 306-311, IOP Publishing Ltd, UK.

(20) Raps, F. et al.:
Theoretische Untersuchungen und Experimente im Labor zur aktiven Dämpfung von Bauwerksschwingungen.
Optimale Auslegung von Schwingungsdämpfern zur Schwingungsberuhigung elastischer Strukturen.
VDI Berichte 627. VDI Verlag ISBN 3-18-090627-8, Düsseldorf, 1987.

(21) Lammering, R.:
The Application of a Finite Shell Element for Composites Containing Piezo-Electric Polymers in Vibration Control.
Computers and Structures, Vol. 41, No. 5, pp.1101-1109, 1991, UK.

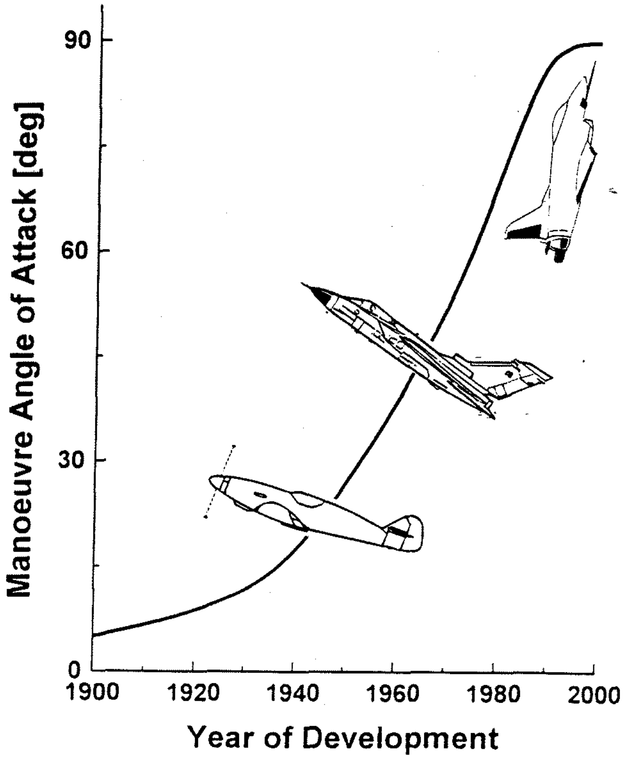


Fig. 1: Trend for the Manoeuvrability Increase of Fighter Aircraft

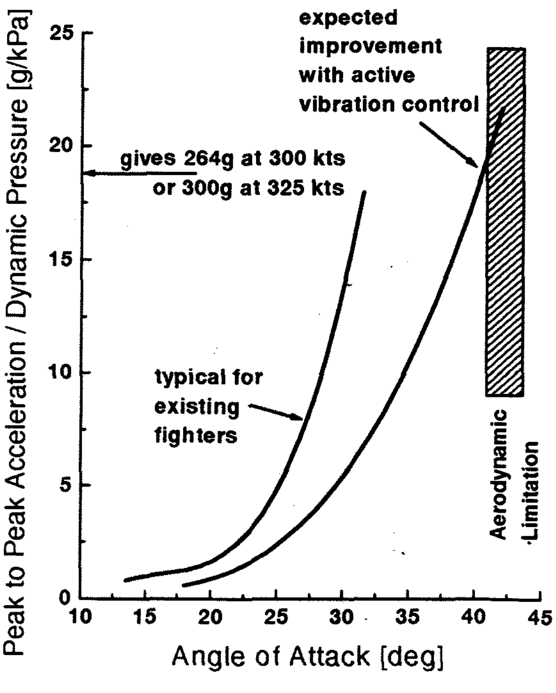


Fig. 2: Typical Fin Tip Acceleration with Increasing Angle of Attack for Current Fighters and Expected Improvement by Active Control Technology

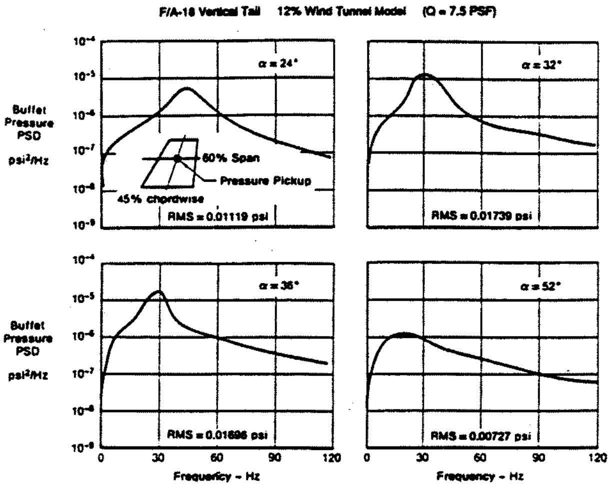


Fig. 3: Variation of Buffet Pressure with Angle of Attack (Adapted from Fig. 6 of Ref. (3))

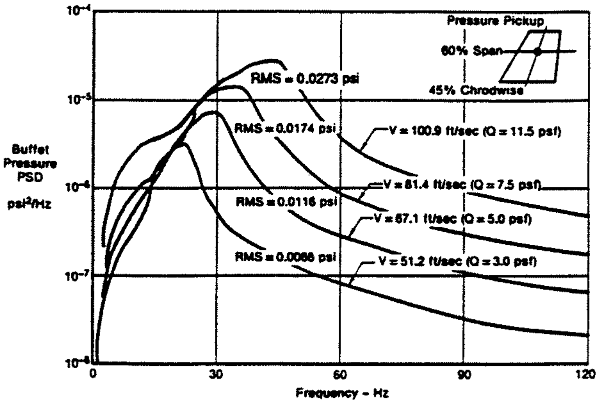


Fig. 4: Buffet Pressure Scaling with Airspeed (Adapt. from Fig. 7 of Ref. (3))

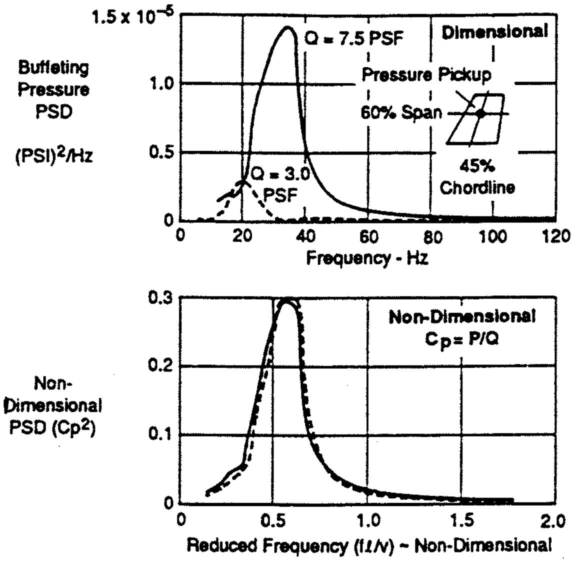
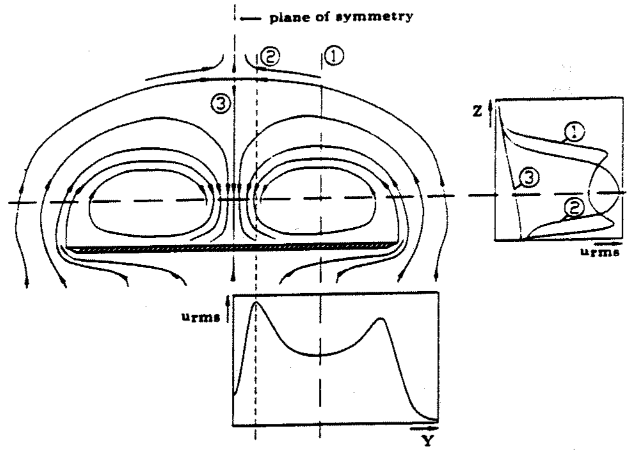
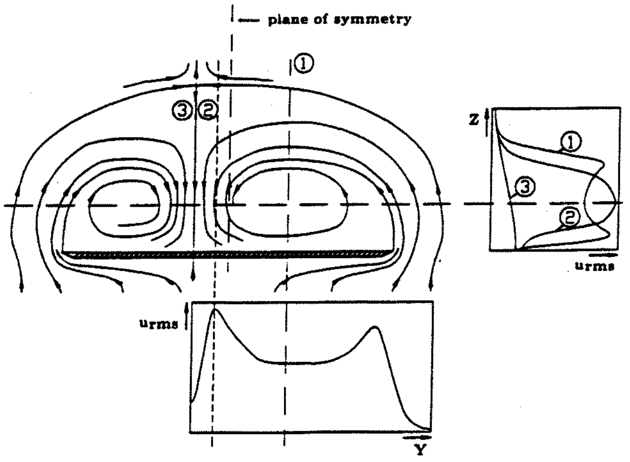


Fig. 5: Normalized Dimensionless Pressure vs. Reduced Frequency (Adapted from Fig. 8 of Ref. (3))

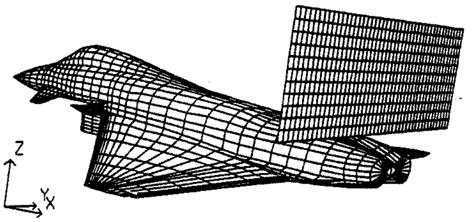


a) Transverse flowfield and rms profiles at $\alpha \approx 30$ deg and no sideslip

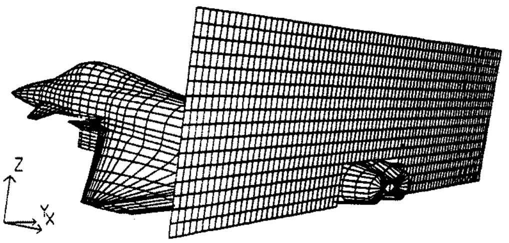


b) Transverse flowfield and rms profiles at $\alpha \approx 30$ deg and sideslip

Fig. 6: Flow Characteristics at 30 deg. AOA with and without Sideslip Angle (Adapted from Fig. 11 of Ref. (6))



a) Standard plane



b) Large plane

Fig. 7: Location and discretisation of Measurement Plane (Adapted for Fig. 2 of Ref. (6))

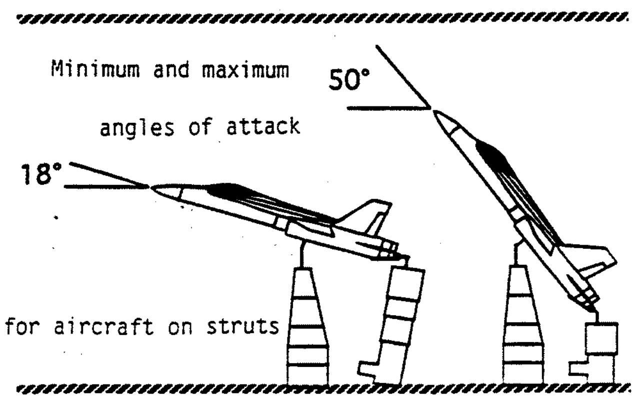


Fig. 8: F/A-18 Installation in NASA-Ames Full Scale Wind Tunnel (Adapted from Fig. 5 of Ref. (5))

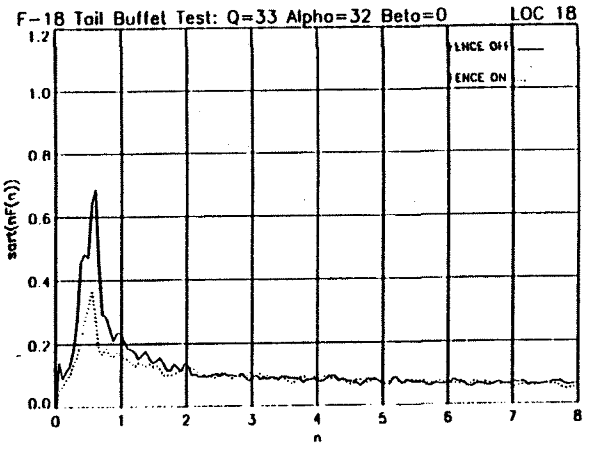


Fig. 9: Nondimensional Pressure PSD at 32° AOA (Adapted from Fig. 27 of Ref. (5))

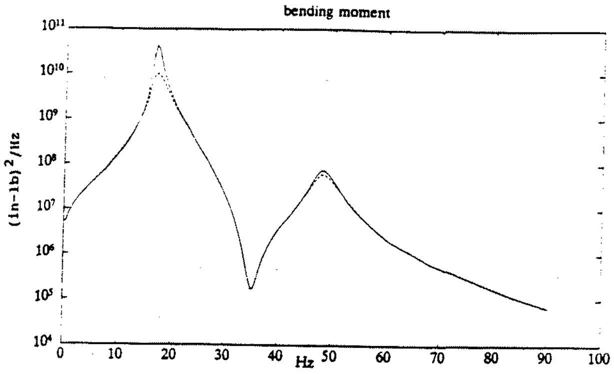


Figure 18. PSD of F/A-18 fin root bending moment due to buffeting at $\alpha = 32^\circ$, $q_\infty = 300$ psf, sea level. Solid curve is open-loop; dashed curve for fin-tip acceleration feedback to cause RMS $\delta_R = 3.2^\circ$.

Fig. 10: Open and Closed Loop Fin Root Bending Moments at 32° AOA and q=300psf. (Adapted from Fig. 18 of Ref. (4))

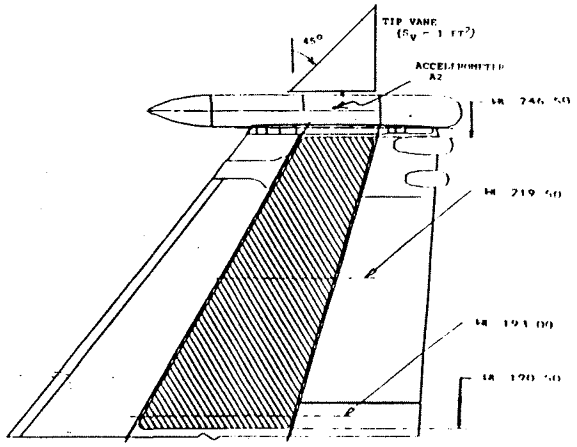
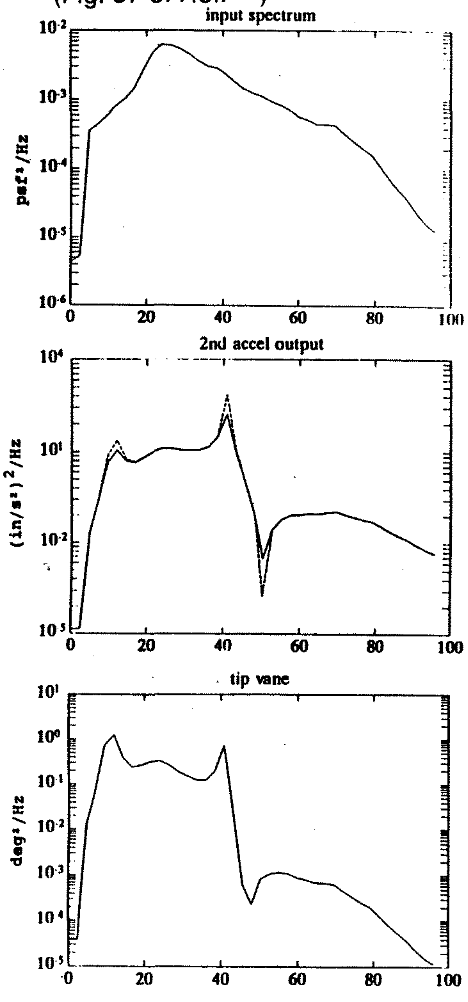


Fig. 11: Fin Tip Vane Used for F-15 Study (Fig. 37 of Ref. (4))



Relative Gain	RMS Acceleration at A2 (g's)	RMS Displacement δ_T (deg.)
Open-Loop	45.9	0
0.1	27.6	3.56
0.25	20.59	6.39
0.5	17.3	11.3

Fig. 12: Input and Response Data for Tip Vane Control (Fig. 38 of Ref. (4))

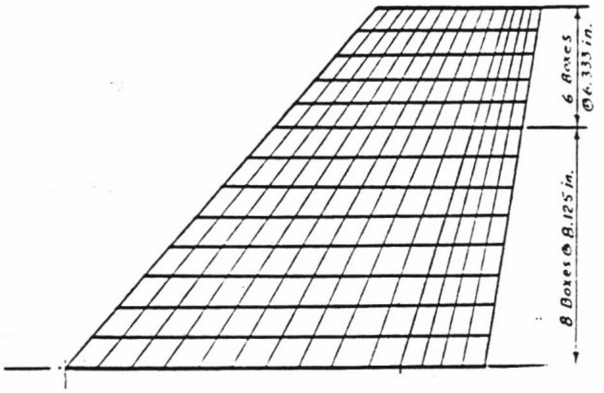


Fig. 13: Unsteady Aerodynamic Model Used for F-18 Study (Fig. 10 of Ref. (4))

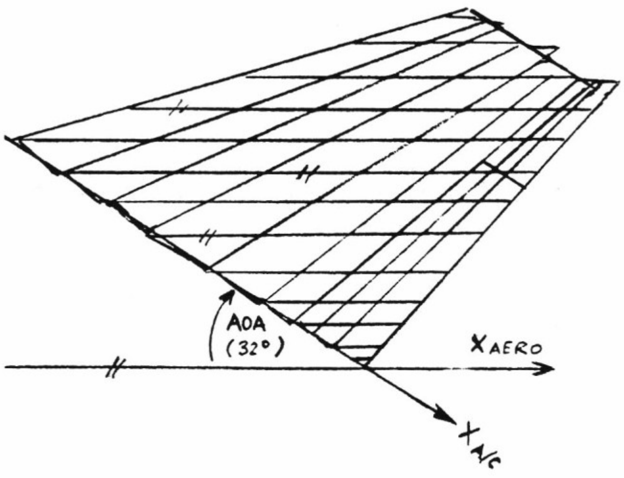


Fig. 14: Modified Aerodynamic Model for Adjust Effects from High Angles of Attack

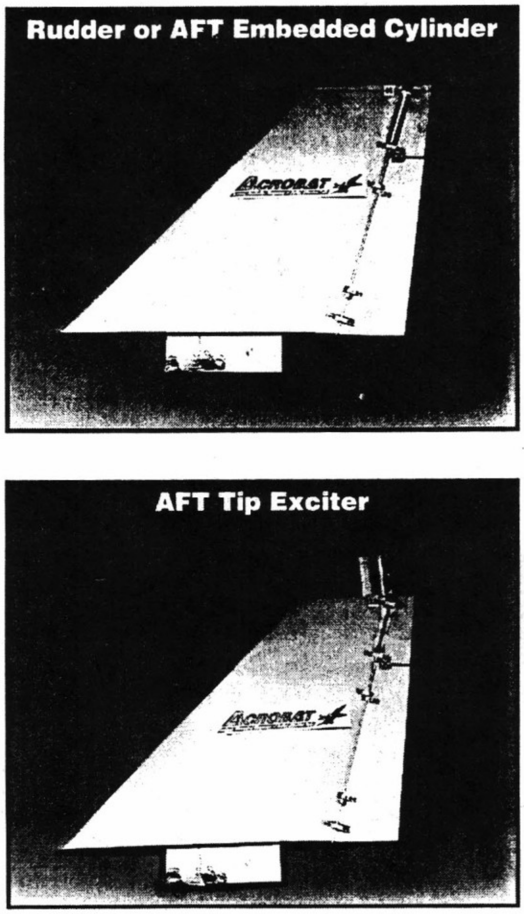


Fig. 15: Configurations for ACROBAT Program

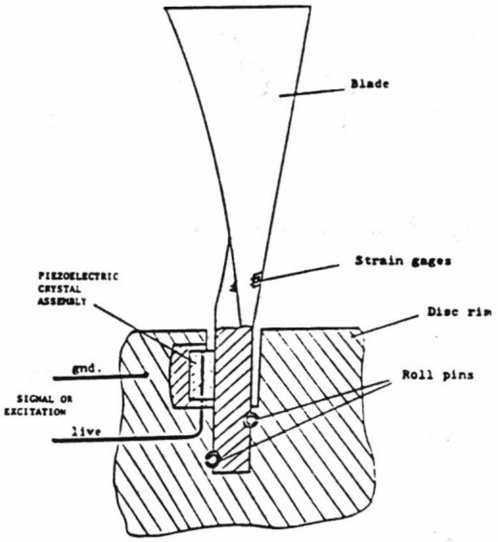


Fig. 16: Early Concept for an Integrated Active Structure Control System (adapted for Fig. 2 of Ref. (11))

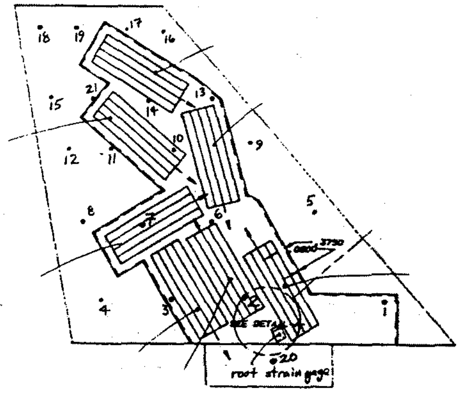
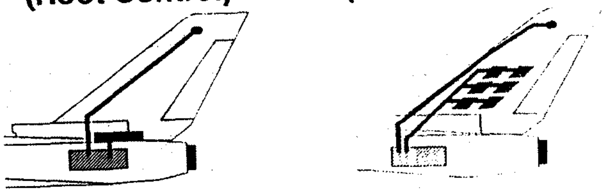


Fig. 17: Structurally Integrated Piezo Actuators of ACROBAT Wind Tunnel Model

Adaptive Interface (Root Control)

Active Integrated Structure (Piezos)



Active Rudder or Vane

Active/Adaptive Mass Damper

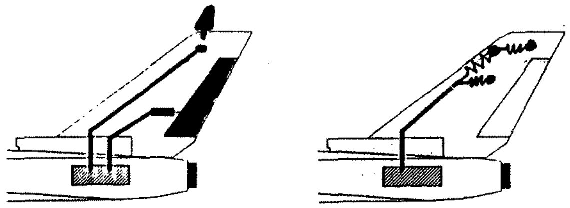


Fig. 18: Main Active Control Candidates for Current DASA Study

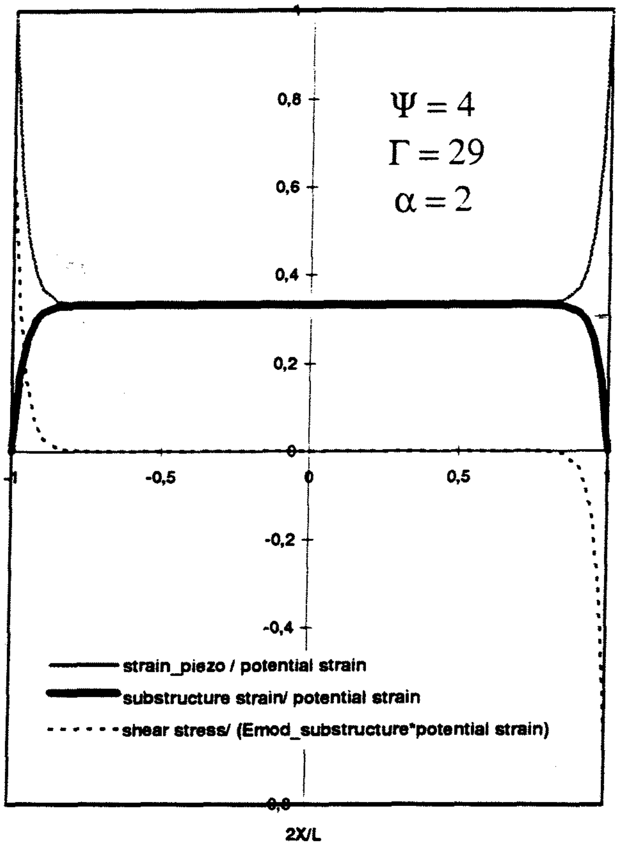


Fig. 19: Strain Distribution along Piezo-Structure Interface

Plate material properties.

	L (mm)	W (mm)	E_L (GPa)	E_T (GPa)	G_{LT} (GPa)	ϵ_{ult} (μstrain)	Λ^*_{11} (μstrain)	Λ^*_{22} (μstrain)	ρ (g cm^{-3})	t (mm)
Steel substrate	n/a	n/a	205	205	77.0	2170	0	0	7.87	var.
Bond	n/a	n/a	23.4	23.4	8.8	n/a	0	0	n/a	0.0508
PVDF	n/a	n/a	2	2	0.75	27 500	231	30.5	1.25	var
PZT-CAP	n/a	n/a	63	63	23.7	1 200	220	220	7.65	var.
PZT-fiber comp.	n/a	n/a	37.5	14.0	3.8	1 200	207	121	4.82	var.
PZT-DAP original	53.9	12.0	63	63	23.7	1 200	220	220	7.65	var.
effo	49.8	2.04	58.19	10.72	21.88					
eff	49.2	1.46	57.55	7.70	21.63					

Table 1: Material Properties for Active Piezo Elements (Adapted for Table 1 of Ref. (16))