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# Active Fin-Buffering Alleviation for Fighter Aircraft

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## ABSTRACT

Severe structural vibrations can be induced in tails of high performance aircraft flying at high angles of attack by vortices originating from wing/fuselage leading edge extensions. The resulting loads may lead to increased material fatigue and require an augmented effort in aircraft maintenance. A number of different concepts have been proposed to either avoid the excitation of the tail fin by bursting vortices or to dampen the resulting structural vibrations. In the early 90s active system concepts were suggested as an efficient way for active buffet load alleviation.

In order to investigate the performance of such systems a collaborative research project was initiated between DaimlerChrysler Aerospace - Military Aircraft Division, the German Aerospace Center (DLR) and DaimlerChrysler Research and Technology within the framework of the Advanced Aircraft Structures Program. Four concepts were investigated in detail within this project:

- An active rudder,
- an active auxiliary rudder,
- a piezo-controlled interface and
- a system of surface-mounted or structurally integrated piezoelectric patch actuators.

The feasibility of all these concepts could be proven and their performance could be assessed in an extensive theoretical analysis that involved the complete aircraft system, as well as in wind tunnel tests on the rudder concepts and, for the piezo-controlled concepts, in tests on a laboratory demonstrator that was conceived, designed and manufactured to be dynamically equivalent to a typical fighter aircraft fin. In addition, a materials qualification program was initiated in order to demonstrate the compatibility of structures with integrated piezoceramic actuators with the requirements imposed through the application in a modern fighter aircraft tail. In this way the maturity of this emerging new technology could be shown and an eventual demonstrator phase was prepared.

## 1. INTRODUCTION

Fin-buffeting is an aeroelastic phenomenon occurring on various high performance fighter aircraft [1, 2]. Flying at high angles of attack vortices originate from the leading edges of wing and fuselage. These unsteady vortices burst drastically near the vertical tail of the aircraft exciting its natural modes. The resulting buffet fatigue loads can become an airframe fatigue and maintenance problem and might require either heavier structures, excessive inspection or active measures to reduce dynamic structural loads.

A number of concepts to reduce the adverse effects of these buffet loads have been discussed in the literature. They range from structural reinforcements of the aircraft tail to aerodynamic modifications along the leading edge of the wing in order to reduce the formation of vortices [3-6]. In the mid-90s active systems for fin buffeting alleviation were suggested and analyzed in the literature [7-9]. Here, damping of the unwanted fin vibrations is achieved by actively controlling the main or an additionally installed auxiliary rudder or by introducing counter-vibrations into the structure through suitable piezoelectric actuators.

Since these studies had shown that active control systems offer a promising solution to alleviate buffet induced strain and increase fatigue life of modern fighter aircraft tails a joint research program in the field of advanced aircraft structures

was initiated between DaimlerChrysler Military Aircraft Division (DASA), DaimlerChrysler Research and Technology (DC-FT) and the German Aerospace Center (DLR). Within this research effort various different concepts for active vibration suppression on vertical fins were developed and investigated theoretically as well as experimentally. Two aerodynamic concepts for buffet alleviation, a rudder and an auxiliary rudder were investigated by DaimlerChrysler Military Aircraft Division [10-12], a piezo-interface concept was studied in collaboration with DLR [13] while a concept with structurally integrated piezoceramic actuators was realized in collaboration with DaimlerChrysler Research and Technology [14-16]. All active systems for vibration damping were designed as digital systems having either an interface to the flight control system (FCS) or being directly part of the FCS [17].

In parallel, a comparable research program was initiated in the United States – with participation from Canadian and Australian institutions – in which an active rudder concept and an integrated piezo concept were investigated for buffet alleviation on the F/A-18 fighter aircraft [18]. In addition to theoretical assessments, wind tunnel tests on a 1/6-scale model of an F/A-18 were conducted at NASA Langley. The project culminated in a full-scale ground test on an actual F/A-18 fin performed at the Aeronautical and Maritime Research Laboratory (AMRL) in Melbourne [19].

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The aim of this paper is mainly to demonstrate the benefits/deficits of each system investigated in the joint DASA, DLR, DC-FT research program by a detailed comparison of the different systems through total aircraft response calculations including the effects of the adaptive control systems. In addition the maturity of the qualification of the structure and of the subsystem fin with piezo-interface and the fin with integrated piezo-ceramic actuators will be demonstrated. In addition the maturity of system integration into the total aircraft system will be assessed.

Therefore for all concepts an investigation and comparison is performed using a total aircraft dynamic model which includes the flight mechanics, the structural dynamics as well as unsteady aerodynamics and a representation of the flight control system together with the active vibration control system for all systems [17]. The total aircraft structural dynamic model as well the unsteady aerodynamic modeling which is applied for the comparison study is updated based on ground test results as well as on flight test results and in one case on wind tunnel results [20]. The controller design considers stability requirements, aircraft dynamic load requirements and flutter requirements.

The rudder concept was investigated using a validated total aircraft model updated by flight test results including in-flight test results for high frequency rudder excitation. The auxiliary rudder concept was validated by wind tunnel tests on a 1/15-scale model of the total aircraft with fin/auxiliary rudder with respect to the unsteady aerodynamic forces of the auxiliary rudder [11-12].

For investigation and validation of the concepts involving either piezoelectric stack actuators attached to the bending bearing or piezoelectric patch actuators bonded to the structure's surface a Fin-Box-Demonstrator (FBD) representing the fighter aircraft fin with respect to structural design and structure dynamics was developed and tested in open and closed loop [14, 16].

Finally recommendations for a flight demonstrator are summarized.

## 2. QUALIFICATION PROCEDURE

A qualification program plan (QPP) was drafted to define the methodology for the qualification of the active buffet load alleviation system. It detailed the specific work packages and methods required for qualification and sets up a timetable for the procedure.

The development of the active vibration control (AVC) system proceeds in several phases with the objective of qualifying it for flight testing. Phase I comprised the technology qualification stage ending with a technology development qualification as a milestone that achieved:

- Definition of a framework of fundamental parameters for the AVC system.
- Experimental and/or analytical demonstration of AVC functionality.
- Experimental and/or analytical investigation of critical specifications and the abidance thereby of the AVC system within the framework of the QPP.

For the active fin buffet alleviation system the QPP identified the following activities that were performed in phase I:

- Theoretical investigation of the performance of each of the four concepts using a whole aircraft dynamic model.
- Scale-model wind-tunnel tests to prove the aerodynamic authority of the rudder and auxiliary rudder concept.
- Laboratory demonstrator tests on a full scale fin box model to prove the actuating authority of the active interface and the structurally integrated piezoelectric actuator concept.
- A materials qualification program intended to demonstrate the compatibility of the AVC system based on distributed surface-bonded or integrated piezoelectric patches as well as discrete piezoelectric stacks with the requirements and specifications for aircraft applications.

The results of these efforts are compiled in section 4 for the four different systems under investigation.

With respect to the system qualification on the complete aircraft initial system level investigations on active buffet alleviation were performed for a limited flight envelope. For the ultimate flight control law development and flight system qualification with an active buffet vibration suppression system the following steps need to be taken:

- Description of aircraft configuration.
- Development of control laws for active buffet load alleviation system. A first definition has already been established within phase I in the context of the complete aircraft model, the definition for the demonstrator will follow in phase III.
- Definition of the complete flight envelope.
- Description of effects and treatment of possible failure modes.
- Development of controller and phase stabilization. In order to prepare design and implementation of the control laws a number of ground and flight tests are necessary. A ground resonance test for the complete aircraft with the modified fin has to be performed to update the computational aircraft model. A ground-based structural coupling test for the complete aircraft with a modified fin with the actuators installed has to be performed to establish the open loop transfer functions for validation of the open loop transfer functions on ground determined from computations. In addition, a flight-based structural coupling test is needed to validate the open loop transfer functions in flight determined through computations.
- Software Development – A first software development plan has been established in phase I. This plan lists all the activities starting with the controller development for the flight control system with an integrated active buffet alleviation system up to the installation of the software and the testing required.
- Demonstration of stability with the active buffet alleviation system.

- Demonstration of flutter stability with the active buffet alleviation control laws.

These activities will all be performed in phase III.

### 3. CONCEPTS FOR ACTIVE VIBRATION SUPPRESSION

A number of active systems for the alleviation of fin buffet vibrations have been suggested in recent years [3-9]. Four promising concepts were selected within the framework of the "Advanced Aircraft Structures" program for further investigation. An active mass damper concept was also considered in the early stages of the program, but was not pursued further due to budgetary constraints. This decision should, however, not be taken as a reason to rule this concept out from future considerations.

In the following, the concepts investigated in more detail shall be described briefly:

#### 3.1 Distributed piezoelectric actuator concept

Wafer-like piezoelectric actuators can induce dynamic strains into structures that can be used to control the shape or reduce vibrations in the structure. Therefore, integrating or surface-bonding piezoelectric actuators across the fin of the aircraft has been suggested as a viable, innovative concept for fin buffet load alleviation (Figure 1). The distribution of the actuators across the most of the fin surface allows to dampen even higher modes. The concept requires provisions for the integration of the actuators in the skin, installation space for the power amplifiers and an added effort in cabling connecting the components.

#### 3.2 Piezoelectric interface concept

The piezoelectric interface induces through a set of piezoelectric stack actuators forces and moments near the location where the fin and the rear fuselage of the aircraft are connected (Figure 2). The actuators will have to be pre-stressed in compression, as they will generally lie close to the static and dynamic load paths. Through its position they will, however, exhibit large actuation authority in particular for the first bending mode. The concept requires some structural modifications to the fin as well as to the rear fuselage section of the aircraft, in order to accommodate the interface as well as the power amplifiers that are necessary for its operation.

#### 3.3 Rudder concept

The rudder concept requires no structural changes to the conventional fin structure except for an eventual modification of the actuator to allow for higher actuation speed. A set of control laws are added to the flight control system to steer the rudder in such a way that aerodynamic forces are excited to counter respectively reduce the buffet loads (Figure 3). This concept can effectively only be used to damp the first fin bending mode, as the inertia of the rudder would prohibit excitation of the rudder at frequencies of the order of the higher modes (above 50 Hz). The benefit of this concept is that it can in principle be implemented immediately with only minor changes to the rudder actuator being required.

#### 3.4 Auxiliary rudder concept

The second active aerodynamic buffet alleviation concept tries to remedy the short-comings of the rudder concept by using a

smaller auxiliary rudder that is steered by a second actuator (Figure 4). By using a small section of the original rudder as the auxiliary rudder with a separate actuator, modifications to the fin structure can be kept to a minimum. For flight control purposes this auxiliary rudder deflects in the same way as the main rudder, whereas in the case of buffeting at high angles of attack, it would generate appropriate aerodynamic forces to alleviate the induced vibrations. The control concept to be employed will basically be the same as for the rudder concept, however, with larger rudder deflections.

### 4. DEMONSTRATION OF COMPLIANCE

An extensive testing demonstration and analysis program was conducted in order to complete the technology qualification stage (phase I) and also a first preliminary qualification stage (phase II) demonstrating a principle compliance of the systems with the specifications that are required. A formal qualification (phase III) was not aspired and will only have to be conducted within the framework of an actual flight demonstration program. However, based on the status achieved in the preliminary qualification valuable conclusions can be drawn with respect to the tasks that still have to be completed for a formal qualification.

The achieved degree of qualification will be summarized in brief in the following sections:

#### 4.1 Distributed piezoelectric actuator concept

As the use of piezoceramic actuators involved the introduction of a new composite material into the aircraft that has so far not been extensively qualified and certified for use in aircraft applications a detailed material qualification program was conceived in order to

- determine material properties of piezoceramic actuators from material samples,
- experimentally characterize actuators and smart composites to provide input data for model calculations,
- perform tests on composite test coupons to demonstrate the conformity of intelligent materials systems with specifications imposed upon them for their integration in aircraft,
- identify, define and perform non-classical tests on smart composite systems in order to test and assure the complete functionality of the intelligent material system,
- develop and demonstrate concepts to integrate smart materials and systems into aircraft design, manufacture and maintenance procedures and processes.

The standardized actuators used in the coupon tests as well as the customized actuator modules on the Fin-Box-Demonstrator were manufactured by Active Control eXperts (ACX) [21] using standard PZT-5A ceramic material. The Fin-Box-Demonstrator is shown in Figure 5. The technology and preliminary qualification extends to the principal design of the actuators, eventual future changes in design or material content may warrant to repeat certain qualification tests.

The following degree of qualification was achieved:

- Coupon tests on ACX QP20N QuickPack™ actuators showed that required **static** structural **strains** above 0.3 %

could be sustained by the actuators. The test was extended to the required temperature range of  $-50^{\circ}\text{C}$  to  $+120^{\circ}\text{C}$  with an insignificant decrease in the sustainable strains at the lower temperature limit. In addition, a structural **fatigue test with passive piezoelectric actuators** subject to dynamic maneuver loads was performed without failure to the actuators.

- An **engineering test** on a specimen equipped with actuator modules was performed to validate the bonding procedure and to identify the failure modes of the smart material system. For this purpose, the actuators were excited at the fundamental resonance frequency of the test specimen for an extended period of time (up to  $30 \cdot 10^7$  cycles). While the bonding interface passed the test without failure, the copper leads within the actuator exhibited fatigue cracks that lead to sparking and short-circuiting.
- A specially devised structural **fatigue test with active piezoelectric actuator modules** subject to maneuver loads was performed showing again the same failure modes as identified in the engineering test. As a consequence, improvements in the design of the actuator modules that avoid these kinds of failures were conceived together with ACX.
- The **power requirements** of the piezoelectric actuators were determined from coupon tests as well as from the experiments on the fin box demonstrator. The **actuator performance** with respect to induced strain and force was determined for varying thickness, length and width ratios between actuator and structure, for plane and curved structures as well as under tensile and compressive loading at various temperatures and humidities.
- The **physical and electromechanical characterization** was completed through a compilation of data provided by the manufacturers and by the measurement of selected properties.
- **Inspection and non-destructive evaluation** procedures were investigated and tested in order to be able to assure the mechanical, electromechanical and electrical integrity of the smart structure continuously [22].
- Concept for planned **maintenance** procedures as well as indicators for non-plannable maintenance were developed.
- Concepts for mechanical and electromechanical **repair** respectively replacement of actuators were developed and shown on the fin box demonstrator.
- The requirements on **aircraft ground equipment** for inspection, maintenance and repair purposes were identified.
- An **installation and integration guideline** was established based on the integration procedure developed on the fin box demonstrator.
- Test coupons exposed to a variety of media and agents present in an aircraft environment showed no deterioration except for traces of **corrosion** of the external copper wires and pins leading to the actuator which can be avoided with standard corrosion protection techniques.
- Problems of **electrostatic discharge** (ESD) will only occur if the actuators with their dielectric surface are directly exposed to the airflow around the aircraft. In an

actual active buffet alleviation system this will in all likelihood be avoided, otherwise standard protection measures against ESD have to be employed.

- The question of **electromagnetic compatibility** (EMC) was addressed in an analysis. EMC tests will be conducted in phase III.
- Passive **aging** tests were conducted on the actuators subject to different temperature and humidity conditions without showing a significant deterioration of electromechanical properties and performance.

The following analyses and system level tests were conducted for the distributed piezoelectric actuator concept [14, 20]:

- Establishment of a complete **finite element (FE) model** with piezoelectric actuators.
  - **Fin-Box-Demonstrator test phase 1** – System identification of the fin box without piezoelectric actuators.
  - **Update of fin box FE model based on test phase 1.** The original FE model showed good agreement with the experiment, an update had only to be conducted with respect to the local CFC panel thickness.
  - **Fin-Box-Demonstrator test phase 2** – Excitation of structural vibrations through piezoelectric actuators. The predicted response levels could be shown.
  - **Update of fin box FEM model based on test phase 2** turned out to be not necessary as the comparison between model predictions and experimental results showed excellent agreement.
  - **Fin-Box-Demonstrator test phase 3/4** – Closed loop damping of the first bending and first torsion mode. The load alleviation due to a simulated buffet excitation compared well with the values predicted by the model.
  - Based on the results of the Fin-Box-Demonstrator model predictions and experiments a **complete aircraft model** with integrated piezoelectric actuators distributed across the skin was established. Open loop transfer functions (IMU output to actuator input) were analyzed with the dynamic model of the aircraft. Control laws were determined based on the open loop transfer functions and power requirements for the buffet alleviation system were documented.
- #### 4.2 Piezoelectric interface concept
- As the use of piezoceramic stack actuators in the piezo interface concept involved the introduction of a new material and actuator into the aircraft a detailed material qualification program had to be conceived just as in the case of the structurally integrated distributed piezoelectric actuator concept.
- **Static and dynamic qualification** tests were successfully performed on the stack actuators based on the expected operational loads at room temperature and at  $120^{\circ}\text{C}$ .
  - An **engineering test** simulating buffet loads was performed where the actuators were excited in resonance for an extended period of time subject to various static pre-loads.

- Short-circuiting caused by an electrical breakdown between adjacent electrodes was identified as the major **failure mechanism** in the stack actuators.
  - A qualification test was performed on the structure subject **maneuver loads** with active interface in open and closed loop operation. The results confirmed the findings of the engineering tests.
  - The **power requirements** of the stack actuators were determined from the resonance test. The actuator performance with respect to induced strain and force was determined for various temperatures.
  - The **depolarization pressure, as well as tensile, shear and bending strength** were quantified using manufacturer's data. Due to the large variations in the data some experimental checks should be performed for the demonstrator phase. The axial strength has been investigated for various stack actuators. In addition, experience from qualification tests according to ESA guidelines with respect to random vibration, vacuum temperature cycling and shock testing have also been considered.
  - **Shear and angular compatibility** of the stack actuators do not pose a problem due to the configuration of the interface.
  - The **physical and electromechanical characterization** was completed through a compilation of data provided by the manufacturers and by the measurement of selected properties.
  - Concepts for **maintenance** were analyzed. In addition, the integration of the adaptive interface into a composite health monitoring system as it was developed in the different work packages of the "Advanced Aircraft Structures" program would provide a maintenance indicator that could point out failures not only in the interface but also on the aircraft fin itself [23]. This provides an effective **inspection** method for both the interface system and the fin.
  - **Repair** - due to the modular design of the interface, defective stacks could quickly be replaced.
  - Special **aircraft ground equipment** is not required.
  - An **installation and integration guideline** was established based on the integration procedure developed on the fin box demonstrator. Alterations in the design of the rear fuselage of the aircraft have to be expected with the integration of the interface.
  - Compatibility of the system with different agents and media present in the aircraft environment as well as with different levels of humidity will be investigated in phase III. The metallic parts of the interface have to be protected against **corrosion**. The electrical and electromechanical components are protected against corroding agents through their protective and electrically isolating coating.
  - Problems with **electrostatic discharges (ESD)** has to be prevented in the aircraft through suitable standard protection procedures. In the qualification tests a suitable grounding strategy was pursued to carry away electrostatic charges that may build up.
  - The question of **electromagnetic compatibility (EMC)** was addressed in an analysis. EMC tests will be conducted in phase III.
  - Passive **aging** tests were conducted on the actuators subject to different temperature conditions without showing a significant deterioration of electromechanical properties and performance.
  - In connection with space applications the behavior of piezoelectric actuator components in vacuum were tested on a material level. If suitable components are selected, no **toxic emissions** are to be expected during operation.
- The following analyses and system level tests were conducted for the distributed piezoelectric actuator concept:
- Establishment of a complete **finite element model** with the adaptive interface.
  - **Fin-Box-Demonstrator test phase 1** – System identification of the fin box without piezoelectric actuators and interface (see chapter 4.1)
  - **Fin-Box-Demonstrator test phase 2** – Excitation of structural vibrations through piezoelectric stack actuators. The predicted response levels could be shown.
  - **Update of fin box FEM model based on test phase 2.**
  - **Fin-Box-Demonstrator test phase 3/4** – Closed loop damping of the first bending and first torsion mode. The load alleviation due to a simulated buffet excitation compared well with the values predicted by the model.
  - Based on the results of the Fin-Box-Demonstrator model predictions and experiments a **complete aircraft model** with the adaptive interface was established. Control laws were determined based on the open loop transfer functions and power requirements for the buffet alleviation system were documented.
- Based on the experiences and results of the interface concept that has been investigated within the framework of the "Advanced Aircraft Structures" program a more efficient interface concept was conceived, that promises significant improvements concerning weight, volume and installation location as compared to the original concept.
- #### 4.3 Rudder and auxiliary rudder concept
- As the rudder and auxiliary rudder concept are based on materials, structures and concepts that are well established in aircraft, only analyses and system level tests based on the validated analytical aircraft model had to be performed. For the rudder itself results from ground and flight tests could be used for model update. For the auxiliary rudder concept the aerodynamic forces had to be determined from wind-tunnel measurements at the Technical University of Munich ([11-12]). The 1/15-scale wind-tunnel model is shown in Figure 6.
- The following analyses and system level tests were conducted for the rudder concept:
- A **complete aircraft model** with the rudder was established. Control laws for the rudder concept were determined and power requirements for the buffet alleviation system were documented.

The following analyses and system level tests were conducted for the auxiliary rudder concept:

- Establishment of a **finite element model** for the wind-tunnel model with auxiliary rudder.
- **Wind-tunnel tests for the auxiliary rudder concept phase 1** – Excitation through the auxiliary rudder for angles of attack of up to 31 degrees. These experiments conclusively demonstrated the assumptions about the aerodynamic phenomena that had been used in the control law design as well as the effectiveness of the auxiliary rudder at least up to an angle of attack of 31 degrees.
- **Update of the fin FE model based on test phase 1.**
- **Wind-tunnel tests for the auxiliary rudder concept phase 2** – Excitation of the fin through buffeting, auxiliary rudder for vibration damping (closed loop testing). A reduction of the fin-tip acceleration caused by buffeting of 60 % could be shown for the closed loop control for all angles of attack up to 31 degrees.
- **Update of the fin FE model based on test phase 2.**
- A **complete aircraft model** with the rudder was established. Control laws for the rudder concept were determined and power requirements for the buffet alleviation system were documented.

## 5. EVALUATION OF THE CONCEPTS

The goal of designing and developing as well as demonstrating the principal feasibility and functionality of an active fin buffet alleviation system has been reached for all four concepts investigated in detail. The following degree of fulfillment of the qualification requirements has been achieved:

- The preliminary **structure qualification** for the distributed piezoelectric actuator and the piezo interface concept.
- The preliminary **system qualification** for the distributed piezoelectric actuator and the piezo interface concept based on the fin box demonstrator.
- The preliminary **system qualification** for the rudder concept based on ground and flight tests of a modern fighter aircraft for rudder excitation.
- The preliminary **system qualification** for the auxiliary rudder concept based on wind-tunnel tests on a scale model of a modern fighter aircraft with an experimental active vibration control system in closed loop.

Based on the results from the experimental tests and the computational results, the evaluation of the different concepts investigated was pursued using the complete dynamic aircraft model and assuming that the redundant IMU system is used to sense the state of the fin. In this analysis the following findings with respect to the **performance of the systems** were obtained:

- All four active buffet alleviation systems show very similar reductions of the fin acceleration up to an angle of attack of 30 degrees with the same power requirements.
- The distributed piezo actuator concept as well as the auxiliary rudder concept (but not the piezo interface and the rudder concept) show – with the same power requirements – the same reductions of the fin acceleration

for angles of attack between 40 degrees and 50 degrees. This is presumably of interest for an extension of the flight envelope in connection with the use of trust vectoring. A further assessment with respect to the necessity of active vibration control for angles of attack that large has to be based on wind-tunnel tests. For angles of attack above 50 degrees the authority of the auxiliary rudder will be marginal, but in this case fin buffet vibrations are presumably also no longer of importance.

- For the computation of the performance of the different concepts a stiff fuselage structure was assumed. Taking into account the given flexibility of the rear fuselage can as a worst case lead to minor reductions in the buffet load alleviation.
- The piezoelectric interface constitutes a flexible connection of the fin to the fuselage that is governed by the stiffness of the interface. In the experiments on the fin box this led to slight reductions in the dynamic properties of the system – the frequency of the fundamental mode decreased for instance from 18.1 Hz to 16.45 Hz. Modifying the system by increasing the stiffness of the interface – for example, through an increase of the stack cross sections – or by reducing the weight of the fin itself could restore the dynamics of the conventional fin without adversely affecting the performance of the interface.
- The rudder concept is primarily useful for a reduction of low frequency elastic vibrations up to 15 Hz. For higher frequencies – for instance, for the alleviation of the fin torsion mode – the loads on the hydraulic rudder actuator will – due to the large rudder mass – become too high.

With respect to the **structural modifications of the aircraft** that become necessary with the installation of any of the buffet alleviation systems the following assessment has been obtained:

- The distributed piezoelectric actuator concept necessitates the design and construction of a modified fin.
- The piezoelectric interface requires in its original form a modification of the rear fuselage, which in a worst case scenario could alter the dynamic response of the aircraft as a whole. In this case, static and dynamic fatigue test and qualifications for the aircraft would need to be repeated. Based on the experiences and results of the original piezo interface concept a revised design has been conceived that promises significant improvements concerning weight, volume and installation location as compared to the original concept. For the new design, modifications would only be necessary for the fin structure itself.
- The rudder concept does not require any changes of the fin structure.
- The auxiliary rudder concept necessitates the installation of an adequate rudder actuator in the fin.

The following **additional installations in the aircraft** will be necessary in connection with the buffet alleviation system:

- The distributed piezoelectric actuator and the piezo interface concept require an increased effort in cable installation for the actuators as well as additional space onboard for the installation of the power amplifiers.
- The rudder concept does not mandate any additional installations.

- The auxiliary rudder concept affords additional cables running to and from the actuator.
- The distributed piezoelectric actuator concept will lead to a weight increase of about 20 kg at the fin.
- The piezoelectric interface concept also leads to an additional weight increase of about 20 kg at the root of the fin. The weight gain due to a modification of the rear fuselage could not be estimated. The modified interface may bring weight savings as compared to the original concept of up to 70 % and a modification of the rear fuselage would no longer be necessary.

An evaluation of all four concepts was also performed with respect to the **additional design and development effort necessary for integrating the system into the aircraft**:

- All four buffet load alleviation systems considered afford in principle the same effort for integrating their control system into the aircraft's flight control system (FCS). The development of the vibration control system and the qualification of the modified FCS will necessitate a rather large effort as it includes the complete system qualification for all aircraft configurations and flight conditions with the FCS, the qualification on the FCS rig, the flutter and structure coupling qualification through the required ground and flight tests.
  - All four vibration control systems require the actuators to be excited with the correct phase for the respective modes (first fin bending mode, first fin torsion mode, first rear fuselage bending mode, first wing bending mode) in order for a controller to be designed according to stability criteria. The phases of the sensor signals due to actuator inputs are mainly governed by non-stationary aerodynamic forces due to the moving fin, rudder or auxiliary rudder. In flight, so far only the signal due to a rudder excitation up to 15 Hz have been validated. The phase response obtained purely from computations is, in particular for the higher vibration modes, not precise enough for a control system design. Therefore, a buffet load alleviation control system needs to be validated in flight tests before it can be certified.
  - The distributed piezoelectric actuator and the piezoelectric interface concept require an additional development phase for a fail-safe actuator concept and eventually to integrate new more powerful piezoceramic materials as they become available. In addition, both concepts also require a further development phase for power amplifiers that are suitable for the use in aircraft.
  - The aspect of repair and replacement of failed actuators is a specific problem for actuators that are integrated into the structure. If integration instead of surface-bonding is to be considered then suitable repair procedures have to be developed.
  - For the vibration qualification test of the fin with distributed piezoelectric actuators specific requirements and test procedures have to be developed.
  - Concerning higher angles of attack in connection with the introduction of thrust vectoring buffet loads for angles of attack above 30 degrees have to be determined from wind-tunnel measurements in order to assess the dynamic fin loads in the post stall regime.
- For the auxiliary rudder concept, it is necessary to perform wind-tunnel experiments for angles of attack above 30 degrees in order to evaluate the efficiency of the auxiliary rudder in this regime.

## 6. RECOMMENDATIONS

Based on the results of the research effort on active buffet alleviation systems for modern fighter aircraft the following recommendations are made:

- Advanced aircraft flight tests have indicated the presence of large vibration loads in the first fin bending mode when the airbrake is engaged. A demonstrator program to show the alleviation of the airbrake-induced fin vibrations could be implemented immediately for the **rudder concept** by including the lateral phase stability concept into the current flight control system without any modifications to the fin. (Short-term recommendation)
- The auxiliary rudder, piezo interface and distributed piezoelectric actuator concept have all exhibited considerable promise for the active suppression of fin buffet alleviation at large angles of attack up to 32 degrees. A demonstrator program employing one or more of these concepts should be implemented to show their viability for buffet-induced fin vibrations in flight tests. This would imply the completion of the remaining phase III tests to qualify the systems for the demonstrator flights. A decision on the system(s) to be implemented on an actual aircraft has then to be made based upon the complete test and analysis results. (Intermediate-term recommendation)
- If buffet-induced fin vibration loads become larger with angles of attack above 32 degrees, then one of the active buffet-load alleviation concepts could be implemented on thrust vector flight programs. (Intermediate-term recommendation)
- The technologies developed in the context of buffet load alleviation should be transferred into future military aircraft concepts – such as for instance UAVs – as well as to civilian aircraft and helicopters for active vibration suppression systems. (General recommendation)

For the concepts using piezoelectric actuators some additional development efforts could facilitate the introduction of these technologies into actual products significantly:

- Advances in actuator technologies to obtain more efficient and fault-tolerant actuators and in material development to have larger active strains available – for instance through the use of single-crystal ceramics or phase switching materials – need to be pursued vigorously to improve the actuator authority for vibration control applications.
- Concepts to integrate the actuators into the structure to allow for cost-effective manufacturing procedures need to be developed.
- Control electronics and in particular power amplifiers need to be improved with respect to their efficiency, their performance, their weight and their integrability for these systems to see more widespread use in aerospace applications.

## 7. SUMMARY AND CONCLUSIONS

Within the "Advanced Aircraft Structures" program four concepts for active buffet-load alleviation were investigated in detail. Benefits and drawbacks of the implementation of the individual concepts were assessed. A preliminary system qualification was performed for all these concepts, laying the foundation for an eventual flight demonstrator program that could show the viability and the benefits of such an active buffet-load alleviation system in the environment of the actual application.

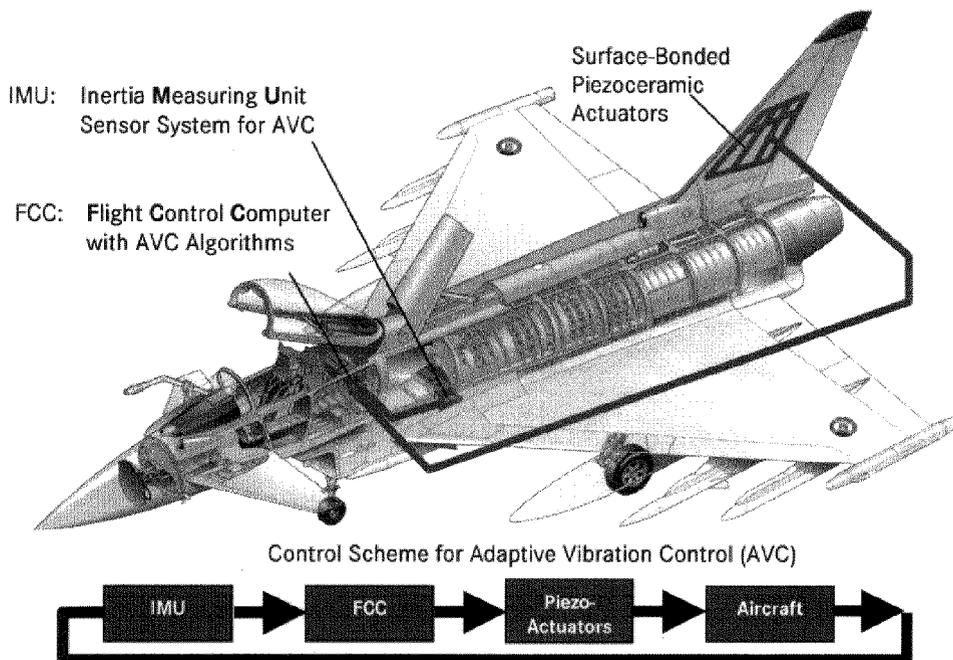
## 8. ACKNOWLEDGEMENTS

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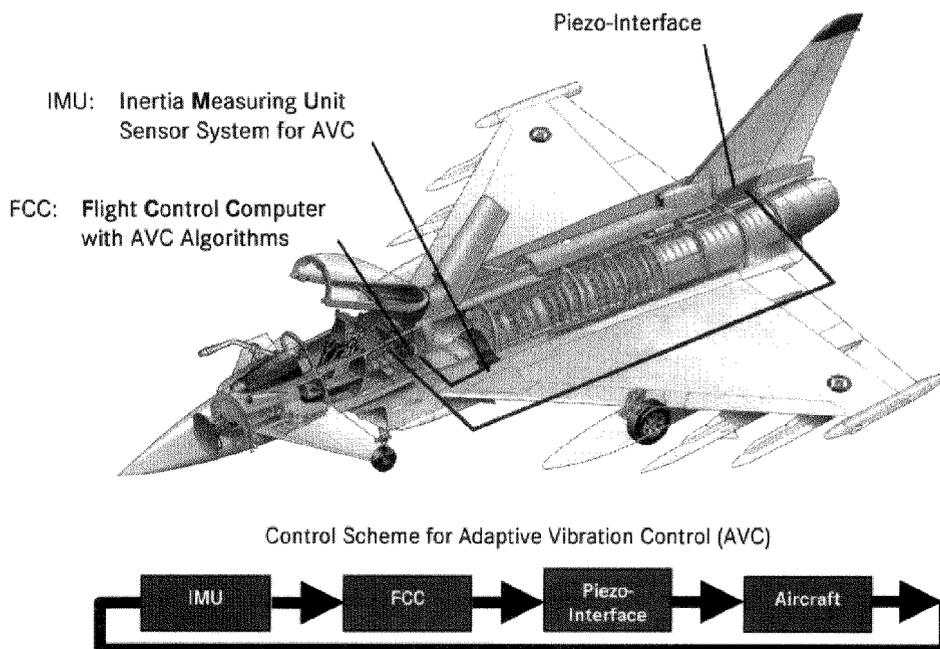
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10. FIGURES



**Figure 1:** Adaptive fin vibration control using surface-bonded piezoceramic actuators.



**Figure 2:** Adaptive fin vibration control using a piezoelectric interface.

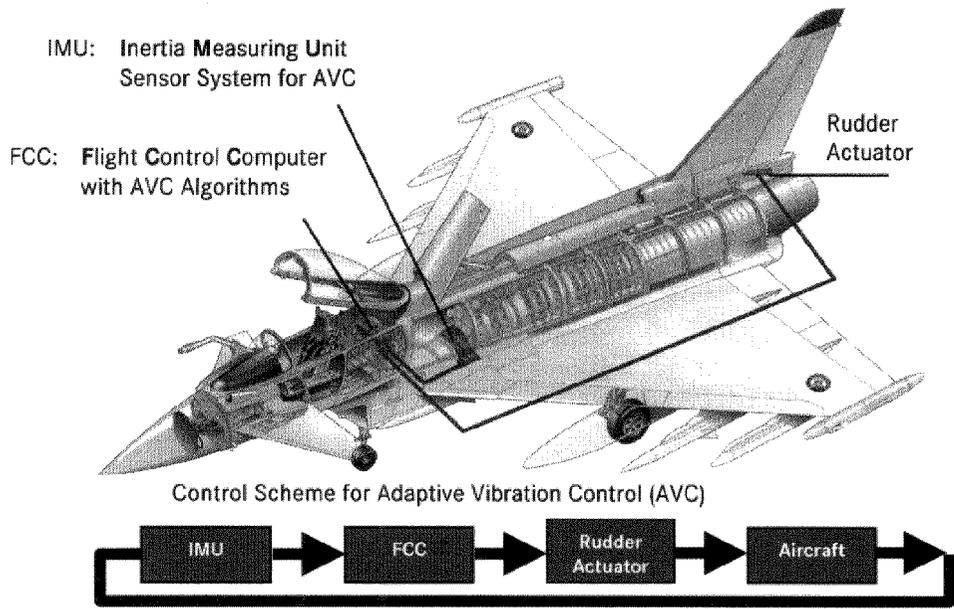


Figure 3: Adaptive fin vibration control using adaptive rudder steering.

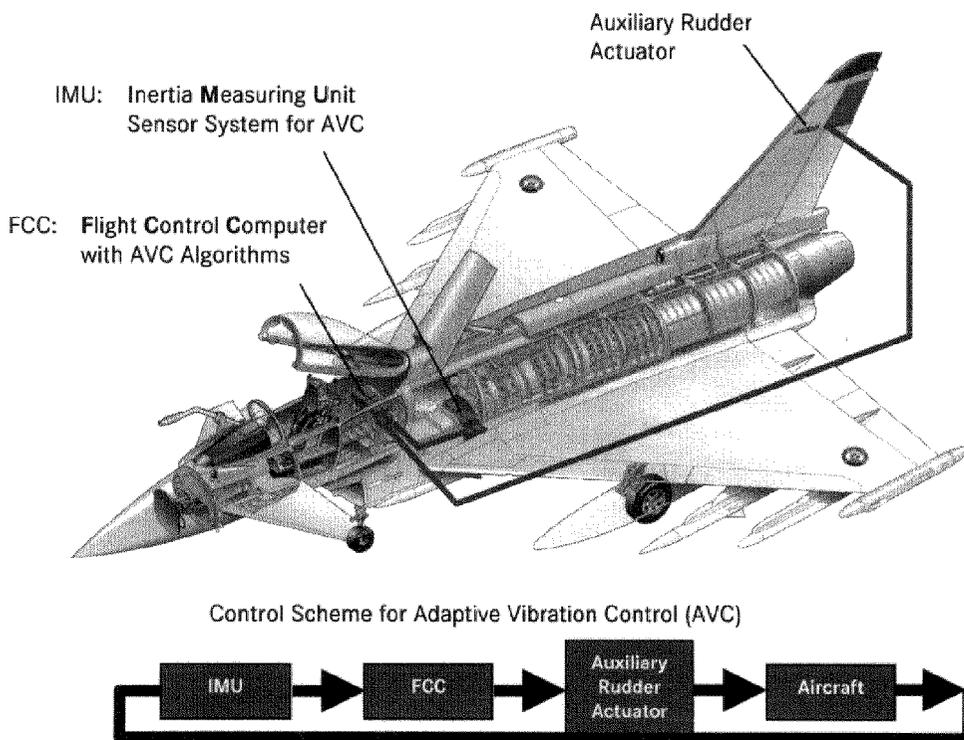
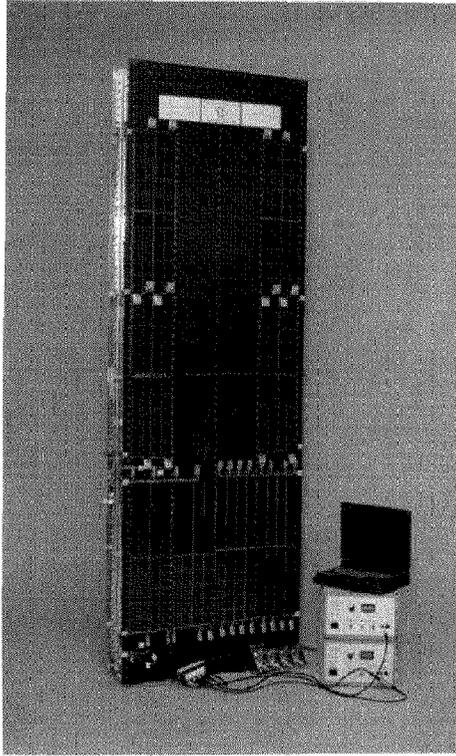
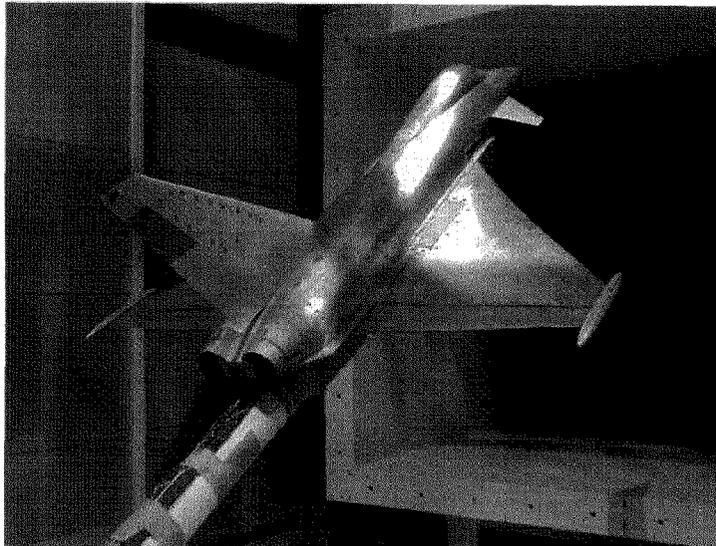


Figure 4: Adaptive fin vibration control using adaptive auxiliary rudder steering.



**Figure 5:** Fin-Box-Demonstrator [2000 x 700 x 156 mm<sup>3</sup>] to demonstrate the distributed piezoelectric actuator concept and the piezoelectric interface concept.



**Figure 6:** 1/15-scale wind-tunnel model to demonstrate the auxiliary rudder concept.

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