Smart Structures and Systems, Vol. 1, No. 2 (2005) 159-184
DOI: http://dx.doi.org/10.12989/sss.2005.1.2.159

The future role of smart structure systems in modern aircraft

J. Becker†

EADS Deutschland GmbH, Military Aircraft, 81663 München, and Technical University of Munich, Institute of Fluidmechanic, Germany

W. Luber‡, J. Simpson‡† and K. Dittrich‡‡

EADS Deutschland GmbH, Military Aircraft, 81663 München, Germany

(Received July 28, 2004, Accepted March 25, 2005)

Abstract. The paper intends to summarize some guidelines for future smart structure system application in military aircraft. This preview of system integration is based upon a review on approximately one and a half decades of application oriented aerospace related smart structures research. Achievements in the area of structural health monitoring, adaptive shape, adaptive load bearing devices and active vibration control have been reached, potentials have been identified, several feasibility studies have been performed and some smart technologies have been already implemented. However the realization of anticipated visions and previously initial timescales announced have been rather too optimistic. The current development shall be based on a more realistic basis including more emphasis on fundamental aircraft strength, stiffness, static and dynamic load and stability requirements of aircraft and interdisciplinary integration requirements and improvements of integrated actors, actuator systems and control systems including micro controllers.

Keywords: health monitoring systems; equipment vibration alleviation; dynamic load/vibration suppression; semi active variable stiffness; passive and active aerodynamic shape/contour control.

1. Introduction

Smart aircraft structure systems are an extension of the classical structure systems which are defined only by structures and loads characterized by aeroelastic and aeroservoelastic structures.

Fig. 1 demonstrates the interaction of Structure & Aerodynamics, Sensor & Actuation & Control to be considered in smart structure design.

Special types of smart structures exist, which consider only the interaction of structure and aerodynamics to optimize aircraft performance. These types of smart structure, which are indicated in Fig. 1 as aeroelastic structures, are passive or semi passive systems which provide under load optimum

†Dr. ing., Corresponding Author, E-mail; juergen.becker.external@eads.com and becker@flm.mw.tum.de
‡Dipl. ing., E-mail: wolfgang.luber@eads.com
‡†Dipl. ing., E-mail: john.simpson@eads.com
‡‡Dipl. ing., E-mail: kay.dittrich@eads.com

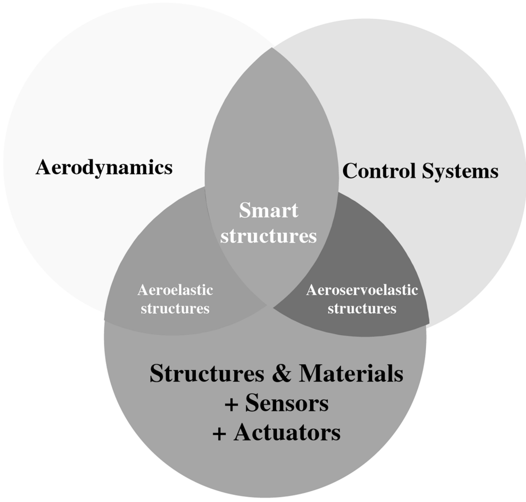

Fig. 1 Smart aircraft structure systems - consideration of interaction of structure/materials & aerodynamics, sensor& actuation & control

torsional deflection and therefore improved performance or provide vibration and dynamic load alleviation. An extension of the so-called aeroelastic structures are the so-called aeroservoelastic structures. They are identical to the aeroelastic structures, however they contain in the aerodynamic loads in addition the effects of the flight control or other control systems of the aircraft.

Other special types of smart structure systems do not fully consider at present the interaction with aerodynamics, control systems and actuators. These types of smart structure are characterized by integrated sensor systems for the purpose of health monitoring, manufacture monitoring and failure detection.

The active and adaptive smart structure systems for shape/contour control of aircraft and aircraft vibration control take into consideration all interactions as demonstrated in Fig. 1.

Here some of the actual and future development of the different kind of smart structures of EADS Military aircraft is briefly described. Structural Health Monitoring systems, manufacture monitoring systems, integrated antenna systems are mentioned. Semi active and active aerodynamic and shape/ contour control systems, aerodynamic flow control via shape control of main aircraft components, results of wind tunnel measurements of wing with formvariable trailing edge and structural concepts of formvariable wing trailing/leading edge are described. In addition adaptive equipment vibration suppression systems and adaptive airframe vibration suppression systems might be considered during design of future smart aircraft structure systems. It is not intended to present a complete summary of the research in German military aircraft industry. Only some important aspects of the actual progress in EADS German Military Aircraft Company, especially of the air vehicle structural technology branch are outlined.

2. Structural health monitoring – manufacture monitoring

There is a variety of advanced sensing technologies available and emerging on the market, via which in combination with miniaturized electronics- micro controller, computer power and signal processing make on-condition monitoring of structures more attractive, (Dittrich, *et al*. 1999, Kaiser, *et al*. 1999). Monitoring has become imperative as a consequence of damage tolerant design in aerospace and the procedures established today are still limited to using electrical strain gauges for monitoring load sequences and handhold ultrasonic and Eddy-current devices in excess of visual inspection in damage monitoring respectively. Even with aero-structures designed safe life, such as the Eurofighter Typhoon, a loads monitoring system is required, because flying to the limits with fighter airplanes as well as allowing for modifications of the aircraft along the aircraft's operational life will result in a damaging behavior of the structure different to the way it has been designed initially. Further to this the introduction of advanced materials such as composites has not allowed to take full advantage of their damage-tolerance and thus light-weight potential due to the fact, that their damaging behaviour is still not fully understood. Even with conventionally designed metallic airframes a variety of damage tolerance design constraints exist which are driven by the fact that there are locations in the airframe, that cannot be inspected sufficiently by traditional means. An automated structural health monitoring system such as based on smart technologies is therefore a solution to this problem highly worth to be considered, which may result in weight savings easily paying off the additional investment for the smart monitoring system.

For loads monitoring, fibre optic Bragg grating (FBG) sensors have shown to have a significant advantage when compared to the traditional electrical strain gauges. While electrical strain gauges require wiring for each of the sensors separately, FBG sensors can be aligned in hundreds and even beyond one thousand along a single optical fibre of 150 am in diameter. Since each sensor responds on an individual frequency band the relative shift in each sensor's wavelength can be taken as a measure for strain or anything else being related to it such as temperature or pressure. FBG sensors are furthermore not affected by any electromagnetic interference, are light-weight and can be integrated into composite materials. However even as surface mounted sensors they show sufficient resistance with regard to varying operational conditions. Proof of operation has been shown among others with 14 FBG sensors being implemented in the rear pressure bulkhead of the Airbus A340-600 along the major airframe static test where the FBG sensor results have been in full accordance with the electrical strain gauge measurements. Flight tests are now the next step to be followed up.

For damage monitoring links to the traditional non destructive techniques such as ultra sonics and Eddy current are made. Foils with either integrated piezoelectric elements or electrical coils have been developed and tested with the remarkable success that damage such as crack length and corroded areas have been identified in sizes equivalent to those being detected today with traditional techniques. It has turned out that active monitoring techniques, where an acoustic or electrical signal is sent into the structure by an active device have a significant advantage compared to passive monitoring such as acoustic emission, where damage can only be monitored when damage propagates, which is either at very high and thus seldom loads or at a very critical stage where the structure is near to collapse. Combinations of actuation and sensing devices such as piezoelectric elements combined with FBG sensors for applications in electromagnetically sensitive areas or the use of MEMS and annotates are new fields which allow to further structural health monitoring options. The demand profile for inspection changes throughout the lifetime of a military platform. The reasons for this is that the assumption that has been made during the design, development and qualification phases of the platform are based on usage specifications predefined from design and performance requirements of the platform. Life extension programs and modified platform usage (e.g. multi-role usage or weapon system upgrades) change the fatigue life consumption behaviour of the platform, therefore the structural integrity time of the military platform requires individual attention to achieve a reasonably planned operational life as expected during its procurement process (Dittrich, *et al*. 1999).

2.1. Individual load monitoring, testing, diagnosis and prognosis

Fleet-wide knowledge on how an individual usage profile affects the structural integrity of a platform during its operational life-time is important to optimize the total fleet management. Even if the usage profile of a military platform is well understood and stable, its relation to the actual evolution of damage can not be determined, because the individual condition of a specific structural item is subject to scatter from the beginning. Such statistic tolerances are covered by appropriate design and qualification. Additionally, inspections on fleet leaders or even individual platforms help to confirm or adjust the expectations derived from engineering methods or to identify unexpected structural damage phenomena.

By establishing a complete loads history from the beginning of the service for any platform, one could statistically anticipate a probability of damage distribution, which could serve to define statistically supported inspection plans. Testing the structural integrity by inspection should then in theory statistically lead to negative results for the majority of tests. Unexpected findings should be exceptions. A deep knowledge on actual structural integrity is obtained by a combined anamnesis and testing approach, e.g. relating in-service load monitoring with structural inspections. Such comprehensive knowledge is fundamental to appropriate structural diagnosis. Thereby the causal chain for damage evolution can be assessed and integrated into prognostic models for further improved fleet management.

2.2. Testing and disassembly

While data on usage such as flight parameters or load information are gathered under operation of a platform, most of today's testing methods to characterize the state of any platform are used when the platform is available on ground for inspection or maintenance actions: visual inspection or non destructive testing, sometimes requiring a high degree of disassembly. Unfortunately, especially the most accurate means of testing are potentially expensive and time-consuming, such as manual ultrasonic scanning or eddy current inspections. However, sometimes such detailed inspections reveal unexpected damage in unexpected locations. Although these techniques have demonstrated their practicability for a broad variety of applications in different areas: the more accurate they are, the more time they usually need and the more disassembly they could require. Such manual inspection and maintenance tasks can become a real nuisance, especially for tight structural concepts, highly sensitive alloys, geometrical complex or even repaired structural items.

Disassembly is a specific issue. Modern military platforms have a complex structure and are heavily armed with equipment. Direct access to an inspection region is a rare exemption, therefore the effort for disassembly to get the required access is often much higher than the inspection effort itself. Reasons for disassembly are non-structure related reasons for disassembly (e.g. normal maintenance), hidden areas, not accessible for visual inspection (e.g. multi-layer structures), limited range/penetration of visual or NDT inspection (e.g. embedded flaws) and limited resolution of visual or NDT inspection (e.g. small damage initiation).

Whilst it is obvious that the three later draw backs possibly could be overcome by introducing improved testing technologies the first argument is more difficult to tackle. Non-structure related reasons for disassembly (electronics, hydraulics, etc.) could be reduced for example by using equipment or systems with higher mean time between failure (MTBF) and systems with self test capability (built-in test). If the frequency of such scheduled inspections is decreased, a fraction of inspections of structural items cannot take place at the same time, thereby increasing the need for specifically structure-related disassembly.

Eventually a balanced mix of self test function for non-structure systems and "self test" function for structural items could allow significant elimination of a number of scheduled and unscheduled inspections in the future.

Diagnostics are improved tremendously by introduction of high range high resolution modern flexible NDT sensing techniques. Still most of these sensing techniques require direct test access to the structural item. For some cases the sensor function could be built once into the structure to avoid repeated disassembly and optimize such a "remote inspection" process by automation. Avoiding disassembly may also have positive side effects on other systems by reducing the number of rechecks on systems that are not related to structural inspections but are affected by disassembly activities.

In the past, the experience with sensor-based systems that are built into the structure (surface-mounted or embedded) were, despite some success in flight trials (Dittrich, *et al*. 2000, 2003), not really uniquely supporting the idea for a broad instrumentation in practice through sensor failures, calibration issues, additional maintenance, etc. Additionally, the automation of inspection has to meet very high qualification requirements if we want to replace conventional human-in-the-loop inspection procedures by purely sensor-based ones. Most likely the qualification costs grow inflationary with the level of accuracy. But the potential advantages are the considerably reduced human factor, an increased accuracy, an early warning capability, "continuous" monitoring and the possibility of minor repairs instead of major repair or replacement.

The technological need for improved built-in testing as an integral damage detection part of a Structural Health Monitoring System was the common motivation for the Nations that participated in the EUCLID/SOCRATE project, called Active Health Monitoring System AHMOS–"Structural Health Monitoring Systems – Requirements, Design, Realization and Demonstration" (www.ahmos.de), (Kress, *et al*. 2001). Ahmos can be considered as a major step forward for the development of damage detection systems.

Eight damage detection approaches have been selected for further investigation under the AHMOS project based on:

- Acoustic Emission
- Modal Analysis
- Stress-strain variations
- Strain-gradients
- Transversal Shear Stress Release
- HiBi Fiber
- Lamb Wave
- Smart Wide area Imaging Sensor System (SWISS®)

Especially with the SWISS® sensor a major breakthrough has been achieved, as a reliable and cost effective sensor for detecting and monitoring cracks in complex structures is now available (Kress, *et al.* 2001, 2002, 2003).

It is obvious that no single damage detection approach can cover the complete variety of damage types. It may happen that several sensing techniques must be employed on one platform to fulfil the monitoring tasks for different materials, different structural forms and damage types. The more spots there are that have to be monitored and the more damage detection approaches have to be used the more it seems to become unpractical for installation and operation.

What is needed therefore is a flexible modular and distributed system architecture in which different damage detection approaches can be hosted in a practical manner. This can be achieved with appropriate interfaces to individual sensor subsystems that are individually optimized for a specific damage detection approach. This will reduce cabling, improve software and hardware upgrading, but also requires development of a common infrastructure besides the need to develop and prove individual sensor subsystems.

AHMOS (Kress, *et al*. 2003), demonstrated an important step towards future integrated load- and usage-monitoring systems enhanced by damage detection technology. Most damage detection techniques selected in AHMOS each have been tested for a limited number of specific damage types. Besides the need to extend multifunction capabilities and the practicability of implementation, there remains a lot of work to qualify damage detection subsystems to maintain the high level of safety we have today and still achieve a modest but significant net cost benefit. The results of AHMOS will be important to physically integrate anamnesis oriented load- and usage monitoring techniques with built-in structural integrity test systems. Once confidence into damage detection systems has been achieved with existing platforms, structural health monitoring systems can be taken into account for new design and new maintenance and inspection strategies thereby exploiting the full cost benefit potential.

3. Electromagnetic structures

An important and often overlooked aspect of smart structures is the interaction between the external and internal electromagnetic environment, (Berchtold, *et al*. 2001, Dittrich 2000).

The interaction can be passive and active. In the passive sense, a structure can either transmit, reflect or absorb electromagnetic waves. This is not a new aspect, as radomes (transparent structures) and low observable (LO) structures (reflecting or absorbing structures) can be dated back to World War II. What has changed in the last years is the complexity of the structural designs to achieve a specifically matched electromagnetic behaviour.

For radomes, the introduction of wide frequency band sensors and the integration of multiple sensors under one radome has resulted in the requirement for increased broadband performance. On the other hand, the low observable requirements for the airframe make it necessary to match the transparency of the radome to its own operating frequencies as close as possible to avoid unnecessary out of band reflections from the sensor installation. Parallel to the electromagnetic requirements the structural requirements of the platform still apply, which can be quite demanding (e.g. with regard to mechanical loads, temperature, lightning strike or bird impact). The present solution are quite complex multilayer structures (generally made out of composite or ceramic materials) combined with frequency selective surfaces (FSS). Especially FSS, layers with periodic radiating elements (either metallic antenna elements on a dielectric substrate or dielectric slots in a metallic layer) have proven to be a powerful tool to tailor the transmission spectrum of a structure.

A similar situation exists with regard to low observable structures. As in general LO technology slowly looses is character of a “silver bullet” technology with the introduction of counter-stealth sensor systems, the requirements for increased bandwidth coverage and better treatment efficiency are getting more and more demanding. Fig. 2. shows an example of a radar absorbing multilayer structure, showing the complex layer sequence and the achieved broadband absorption curve. In an active way, the electromagnetic behaviour of the structure can either be controlled, or it can actively interact with the environment. One example of controllable electromagnetic structures are tunable radar absorbers. A quite nice example has been demonstrated as early as 1990 (Dittrich, *et al*. 2001). A patented multilayer structure with an integrated network of PIN diodes was developed and tested by EADS. This system called FLIRT (the German acronym for “Area Integrated Electronic Components for Adaptive Radar Absorption”) consists of stacked layers of networks with integrated PIN diodes. The network that forms the frequency selective surface consists of parallel conductive strips. The distance between the strips is

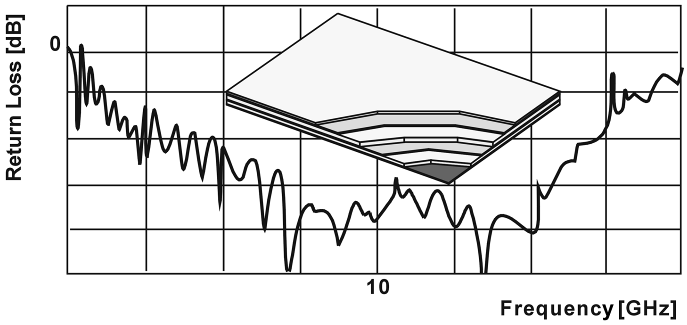

Fig. 2 Return loss curve at normal incidence of a monolithic structure with two resistive sheets developed in the late ’80s. There are two resonance peaks. The return loss values are subject to nondisclosure

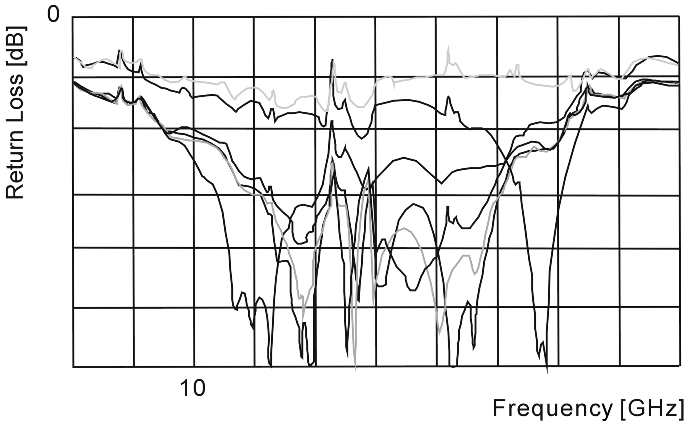

Fig. 3 Return loss curves of the FLIRT demonstrator at different bias current settings. A shift of the resonant frequency over nearly two frequency bands was measured. The return loss values are subject to nondisclosure

small compared to the wavelength. To attain a specific surface impedance, the strips are realized as metal line segments connected by resistor elements. To achieve the desired variation of the surface impedance, PIN diodes are used as resistor elements. The two PIN diode networks, each forming a frequency selective surface, are sandwiched between dielectric layers. The whole stack is backed by a reflector.

If a small bias current is applied, the PIN diode networks change their high frequency surface impedance. By selecting appropriate bias currents, the resonant absorption frequency of the system can be shifted. With the first demonstrator, a shift of the resonant frequency over nearly two frequency bands was measured as shown in Fig. 3. An example for active interaction with the environment are structure integrated antennas. Antenna integration is an area of concern for modern aircraft, as the available surface area is limited and the signature requirements are stringent. Very important are reliable and secure high speed data links, which are crucial for the operation in a networking environment. Conventional antenna integration on present fighter aircraft leads to antenna numbers in excess of 60 different units. The problems associated with this situation are:

- Multiple antennas may be necessary to achieve the required area coverage.
- The smaller the craft, the more problems exist with antenna coupling.
- The area accessible for conventional antenna integration is limited (e.g. tank structures).

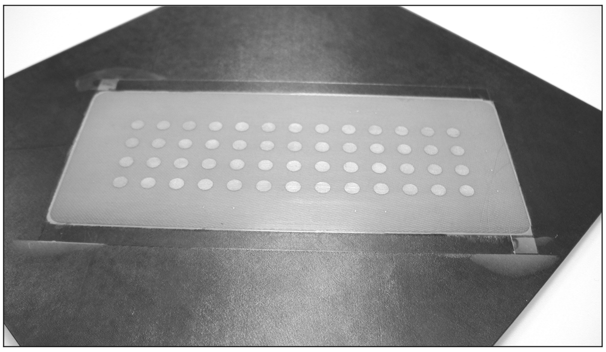

Fig. 4 Example of a structurally integrated antenna. The antenna element is mechanically integrated into a composite primary structure

From the electromagnetic side, there are some tendencies visible to overcome this problem (e.g. shared apertures). Concentrating on the structural side of the story, we would like to distinguish between three different types of antenna integration:

- Bolt-on antennas: the antenna is bolted on the structure and protrudes from the surface (e.g. blade antennas).
- Conformal antennas: the antenna is embedded into a structural cut-out conformal to the outer contour of the aircraft, but is de-coupled from the structural air vehicle loads.
- Structure integrated antennas: The antenna is embedded into the outer contour of the aircraft and is part of the load carrying structure.

Bolt-on antenna solutions usually cause an increased radar cross section, therefore this type of antenna integration is problematic with regard to high LO requirements. In addition to this, they produce additional drag. Conformal antennas usually are easier to treat for reduced signature than bolt-on solutions. Besides that, the aerodynamic efficiency is higher. From the structural point of view, the antenna bay represents a hole in the structure. Therefore, the mechanical loads within the air vehicle primary structure have to be transported around the cut-out by an appropriate support structure. It can be easily imagined that with increased number of conformal antennas the structure may resemble a Swiss cheese (technically speaking a grid framework) more than an effective stressed skin design, thus reducing structural efficiency. In contrast, structurally integrated antennas, as seen in Fig. 4, are characterized as being incorporated into the primary structure skin of the airframe, becoming part of the load carrying structure. This approach reduces the extra weight of the antenna integration considerably while preserving the aerodynamic efficiency of conformal antennas. Another bonus is that the integrated antenna approach promises to make additional surface areas on the airframe available for antenna integration, like the surface of tank structures. From an LO point of view, the integration into the structure eases the LO design, as the number of electromagnetic interfaces is reduced, decreasing the number of secondary scattering centres.

4. Semi active and active aerodynamic and shape/contour control

Flow control is a subject of designers since the first creation of aircraft. In the last decades novel flow control concepts have been proposed and investigated. Some aspects of the novel approach have been described by EADS in the past. The References (Becker, *et al*. 1999, Dittrich 1994, 1998, Dittrich, *et al*.

2004) include an overview of advanced aircraft structures, outline prospects of Smart Structures for future aircraft, concentrate on structural concepts of morphing wing and describe the shape change of wing structures with integrated shape memory alloy actuators.

The different types of aerodynamic systems/concepts are characterized by “active flow control’’, “adaptive flow control’’ and also by “micro adaptive flow control’’. With these technologies in hand enhancement of aircraft performance is expected.

Active flow control is still in a premature state and the development requires a multidisciplinary strategy involving fluid mechanics, active structures, control theory and advanced materials. Highest priority has to be focussed on the development of semi active or active deformable structure systems including new materials and new actuator systems.

Whatever actuation principle with smart technologies may be used, further studies give rise that an adaptive trailing edge of a small aircraft is obviously the solution currently pursued by different organizations where more specific answers are expected to come within the next few years. Besides the investigation of structural concepts, aerodynamic research programs had been initiated in order to demonstrate and validate the benefits with respect to manoeuvre performance, drag reduction, enhancement of aircraft manoeuvre control and aircraft stabilization. Recently performed aerodynamic investigations of adaptive deformable aircraft structures, i.e., optimum aerodynamic shape control of outer wing and leading and trailing edge have been performed with aerodynamic computational fluid dynamic (CFD) simulations and wind tunnel tests on a complete aircraft with different shapes of wing trailing edge. In the past decade EADS Military aircraft division has investigated different structural concepts for actively/adaptive deformable aircraft wing and fin structures. Through the control for example of the local wing twist and camber the optimum local deformation can be achieved also with consideration of controlled aeroelastic deformations at different flight conditions. Feasibility studies of the different structural concepts have revealed significant problems related to system complexity and functionality under environmental conditions and severe problems combined with the development of adequate materials. However novel adaptive structural morphing concepts are now under investigation which might lead to promising way ahead.

Here some aspects of the novel approach are demonstrated and discussed. The conventional trailing edge flap of a wing is replaced by a formvariable trailing edge. The contour of the formvariable trailing edge can be altered by local actuation such that a relative lower drag is achieved and higher pitch and roll moments for aircraft guidance and control are present. Analytical and experimental investigations have been performed to demonstrate and validate the assumption of improved performance of the cambered trailing edge, see (Breitsamter 2003, 2004). In addition different structural concepts of the formvariable cambered trailing edge have been investigated which would enable the shape control. These concept have been developed to a pre-demonstrator status. Some results of the present structural concepts are described below.

Aeroelastic simulations, i.e., coupled structural dynamic response and computational fluid dynamic (CFD) simulations at trimmed flight conditions, have been carried out using the dynamic model of a total aircraft, which is based on the finite element model (FEM). The analytical model of the aircraft was trimmed with conventional trailing edge flap deflections and formvariable trailing edge at high dynamic pressure assuming that the formvariable cambered trailing edge has similar torsional stiffness compared to the conventional flap. From the simulation elastified pitch moment derivatives for the inboard and outboard trailing edge deflection have been derived which show a considerable increase in the moment derivatives, as demonstrated in Table 1.

A comparison of elastified pitch moment coefficient derivatives $dc_M / d\delta_{IB}$ and $dc_M / d\delta_{IB}$ due to

Table 1 Computational fluid dynamic (CFD) simulation – comparison of elastified pitch moment derivatives $da_m/d\delta_{IB}$ and $da_m/d\delta_{IB}$ due to conventional and form variable cambered inboard and outboard trailing edge

Elastified pitch moment derivative	Formvariable cambered flap	conventional flap	Improvement of pitch moment derivative
Inboard flap $dc_M / d\delta_{IB}$	-0.270	-0.236	14.4%
Outboard flap $dc_M / d\delta_{oB}$	-0.176	-0.165	6.6%

inboard and outboard trailing edge for the conventional inboard and outboard flap deflection δ_{IB} and δ_{IB} has been performed. For this purpose the simulation included the derivation of the total aircraft lift and pitch moment, resulting from a constant angle of attack and combined elastic deformation resulting from the angle of attack and trailing edge deflection loads, for the conventional and formvariable case. The comparison of the derivatives was performed on the basis of equivalent lift for both conditions at identical angle of attack but at the different trailing edge conditions.

The improvement of the pitch moment derivatives arises mainly from the effect of shifting the maximum pressure location further down in streamwise direction of the cambered trailing edge flap region compared to the conventional flap at equivalent total aircraft lift, which shows maximum pressure at the hinge line, thus creating a higher pitch moment around the pitch moment reference point, which is the aircraft centre of gravity. This gives indication of the enhancement using formvariable trailing edge control w.r.t. manoeuvring and aircraft stabilization, since the aircraft manoeuvring is dependent on the magnitude of the pitch moment and the pitch stabilization of the aircraft through a flight control system depends on the magnitude of the trailing edge flap pitch moment derivatives $dc_M/d\delta_{IB}$ and $dc_M/d\delta_{oB}$.

Wind tunnel measurements have been performed on a total aircraft model with conventional inboard and outboard trailing edge flaps and formvariable inboard and outboard trailing edge in the low speed wind tunnel of the Technical University of Munich (TUM), see Fig. 5. The figure demonstrates the aircraft wind tunnel model of a modern fighter aircraft with cambered formvariable wing trailing edge in the low speed wind tunnel and shows the different rigid trailing edge segments for the representation of different deflections of the trailing edge used in the tests. The formvariable trailing edge consisted of separate fabricated rigid trailing edges for different deflections shown on the left side of Fig. 5. The model balance allowed to measure total aircraft model lift, drag, pitch and roll moment.

From the measurement results considerable improvements could be demonstrated for the formvariable

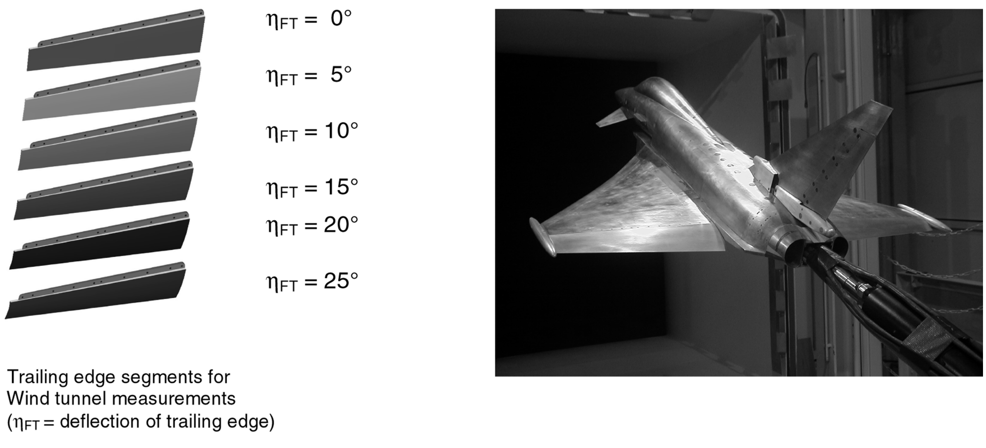

Fig. 5 Wind tunnel test – Model with formvariable cambered trailing edge; $\eta_{FT} = 15^o$ and 25^o

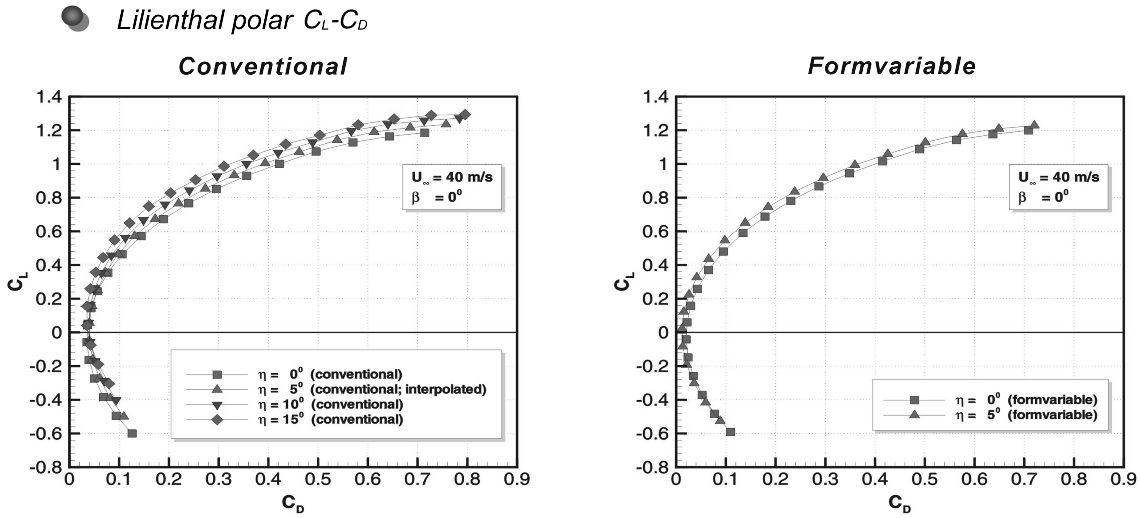

Fig. 6 Comparison of Lilienthal polars C_L-C_D for conventional and formvariable trailing edge – Demonstration of drag C_D reduction using formvariable flap

trailing edge for the investigated range of angle of attack 0 to 32 degrees and different trailing edge deflections 0 to 25 degrees, see (Breitsamter 2003, 2004). Fig. 6 demonstrates the comparison of Lilienthal polars where the total aircraft lift coefficient C_L is depicted versus the total aircraft drag coefficient C_D for conventional and formvariable trailing edge.

The following improvements could be demonstrated through the wind tunnel tests:

- Reduction of drag using formvariable flap - comparison of Lilienthal polars, Fig. 6 and Table 2
- Improvement of pitch control at different lift using formvariable flap, Table 3
- Improvement of roll control at different lift using formvariable flap

The improvements are judged to be the result of the smooth slope of the curvature of the cambered trailing edge region in streamline x- direction, which leads to comparatively low pressure gradients in x-direction.

Table 2 Improvement of drag coefficient ΔC_D at different lift coefficient C_L using formvariable flap

Comparison of drag coefficient C_D				
Lift C_L	Flap conventional 10 deg	Deformed flap at same lift	ΔC_D	ΔC_D[%]
-0.4	0.09344	0.07208	-0.0214	-22,9
-0.2	0.05588	0.03375	-0.0221	-39,6
-0.1	0.04478	0.02337	-0.0214	-47,8
0	0.03930	0.01843	-0.0209	-53,1
0.1	0.03948	0.01917	-0.0203	-51,4
0.3	0.05604	0.03657	-0.0195	-34,8
0.5	0.09482	0.07707	-0.0178	-18,7
0.7	0.16215	0.14853	-0.0136	-8,4
0.9	0.27806	0.26422	-0.0138	-5,0
1.1	0.45687	0.44569	-0.0112	-2,4
1.2	0.57381	0.57785	0.0040	0,7

Table 3 Improvement of pitch control ΔC_M at different lift C_L using formvariable flap compared to conventional flap

Comparison of pitch moment (nose down positive) coefficient C_M				
Lift C_L	Flap conventional 10 deg	Deformed flap at same lift	ΔC_M	ΔC_M[%]
-0.4	-0.12264	-0.11071	0.0119	9,7
-0.2	-0.09874	-0.08292	0.0158	16,0
-0.1	-0.08499	-0.07340	0.0116	13,6
0	-0.07494	-0.06278	0.0122	16,2
0.1	-0.06286	-0.04859	0.0143	22,7
0.3	-0.03198	-0.01599	0.0160	50,0
0.5	0.00577	0.02146	0.0157	271,6
0.7	0.04916	0.06096	0.0118	24,0
0.9	0.09638	0.10401	0.0076	7,9
1.1	0.12592	0.13286	0.0069	5,5
1.2	0.14495	0.15423	0.0093	6,4

4.1. Conclusion from aeroelastic simulations and wind tunnel results

The wind tunnel results demonstrate and validate the benefits with respect to manoeuvre performance, drag reduction, enhancement of aircraft manoeuvre control and aircraft stabilization at low speed. At high dynamic pressure the improvements might reduce due to aeroelastic effects. However as demonstrated by aero elastic simulations there are still significant benefits available at high dynamic pressure. Structural concepts for shape/contour control and control mechanism shall therefore developed with priority.

4.2. Structural concepts of formvariable wing trailing/leading edge

At present the main problems arise for all structural formvariable /shape control concepts from inner wing structural problems due to very high inner forces resulting from the transmission of the trailing edge attachment torsion moment (hinge moment) into very high shear forces which are either present for a special concept in the surface structures and high deformations of the surface structure and in the inner structure (for instance flexible stringers) and ceiling problems of the surfaces resulting from gaps in the surface structure which are caused to generate high deformation, or transmission of the shear forces into the vortex members of another concept. The main driving structural requirement of all concepts is the total weight which should not exceed the weight of a conventional flap system with hydraulic actuator.

Other problems arise due to the fact that existing small electrical or electric/hydraulic actuators which could be integrated into the inner trailing edge /leading structure do not provide high enough forces at the required strokes and stroke velocities which have to be considered for military and civil aircraft applications. Other actuators like piezoelectric elements would fulfil the force and stroke velocity / rate requirements , however are limited to very small elongations which are far too small to generate a concept for military/civil aircraft application. Shape memory actuation would provide sufficient forces and elongations, however are far too slow in order to meet the rate requirements. In order to meet the order of magnitude of force/elongation and rate requirements with the actual status of existing electrical actuators a concept of outer wing actuation has been investigated. Another concept which is able to meet the weight requirement and the order of magnitude of force/elongation and rate requirements for inner wing actuator integration was proposed. This is the so-called tube actuator. The tube actuator concept however is in a very premature stage. For future application in aircraft design this concept needs a very high research effort.

4.3. Trailing/leading edge - actuation outside the wing

Figs. 7, 8 and 9 demonstrate the concept of formvariable wing with external actuators. Both outer and inner wing trailing edge can be deformed up and down using under wing actuation systems at different spanwise sections which consist of a number of small actuators inside a gondola that contract or extend the distance between triangle elements (vortex elements) attached to the wing through pendular supports. Inside the wing flexible stringers transmit the shear forces. Problem areas have been found from analytical and experimental investigations for the flexible stringers at maximum deformation, also the supports of the actuation system at the wing and the ceiling of the wing surface gaps might create problems.

In addition actual available small electrical actuators have small axial limit load, see example in Fig. 10.

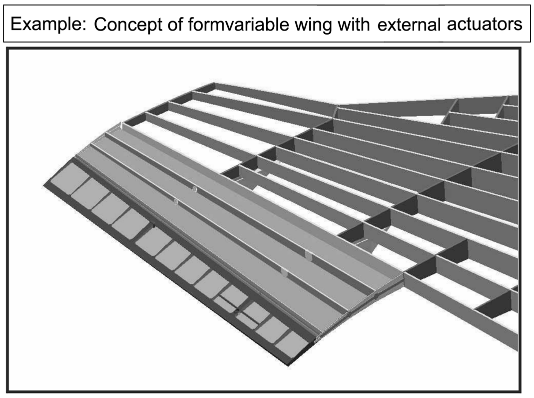

Fig. 7 View of formvariable outer wing trailing edge

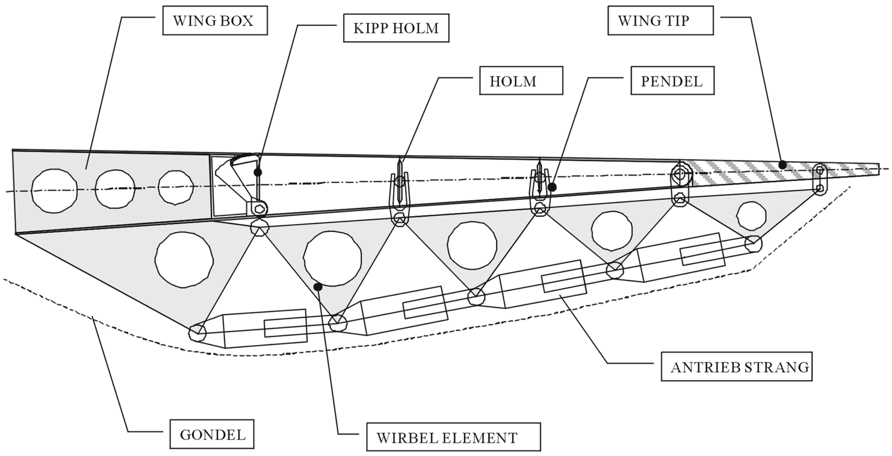

Fig. 8 Outer wing actuator system

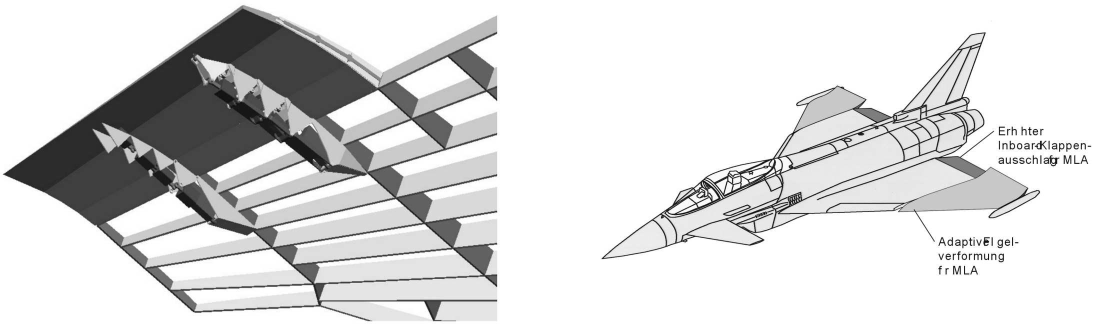

Fig. 9 View of formvariable outer wing trailing edge

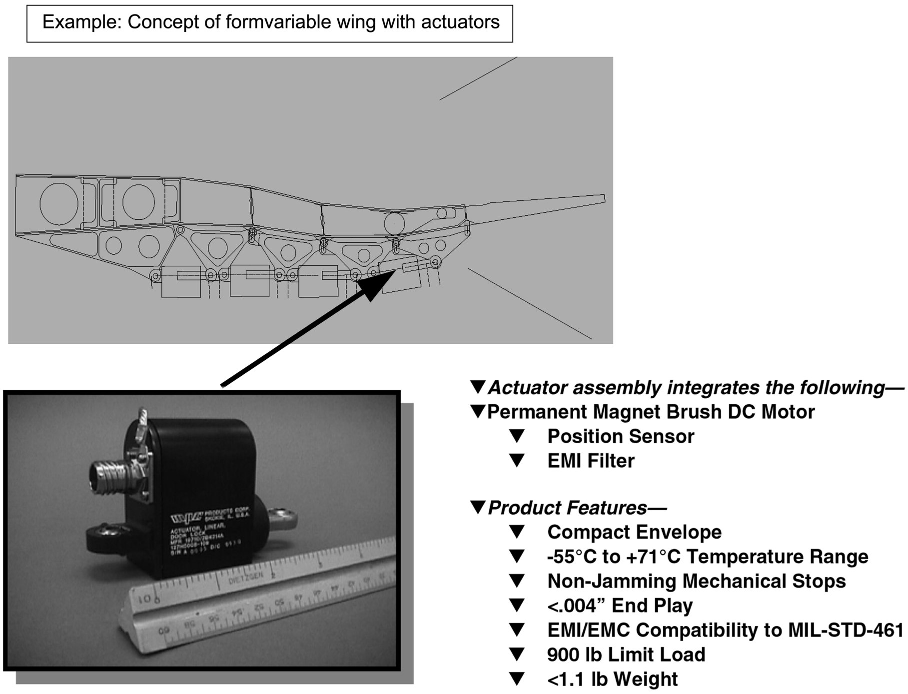

Fig. 10 Typical high power electric actuator with axial drive

4.4. Trailing/leading edge - actuation inside wing

The so-called tube actuator concept is proposed for leading/trailing edge formvariable control. The concept integrates tubes in the upper and lower skin of the leading or trailing edge region of the wing. Through pressure/volume control of the upper/lower skin tubes and combined positive or negative local elongation a certain controlled deformation of the wing can be achieved. Problems might arise from tube material fatigue and safe actuation during entire life. A functional test mock up and a fatigue test shall be performed first to demonstrate performance of the system. Fig. 11 shows the positive and negative deformations for the tube concept achieved on a first demonstrator.

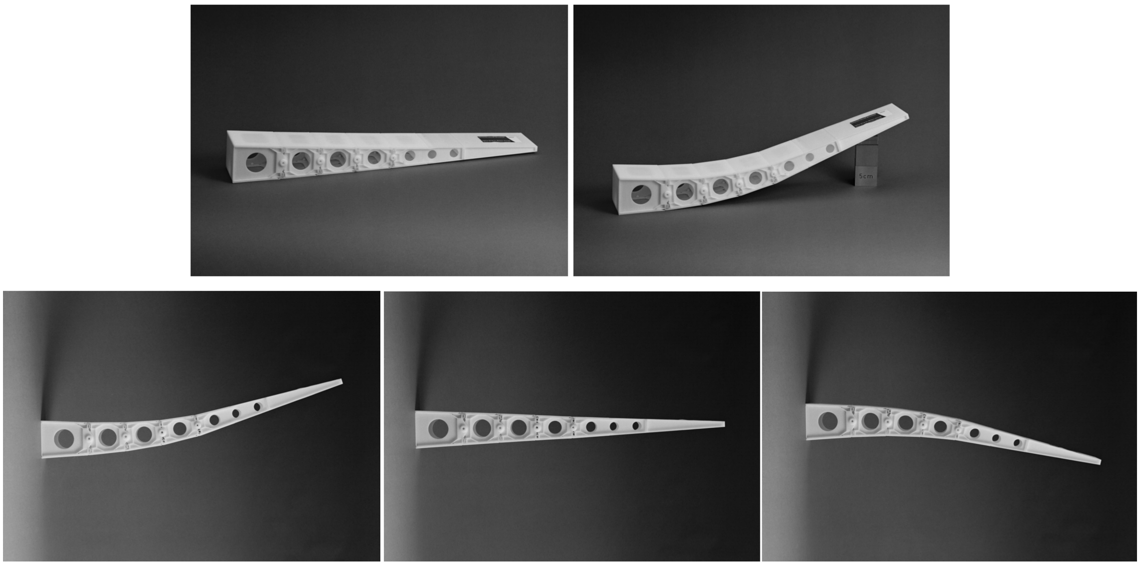

Fig. 11 Tube concept

5. Active and semi active variable stiffness

This area on general terms will be discussed and two aircraft implementation scenarios are selected for demonstration, one active and the second case active with variable stiffness. There has been quite an amount of research on active variable stiffness, using sometimes even ideas of the sixties and even earlier again to new high performance aircraft that now beckon even more competitive efficiency.

- The aim of active and semi active variable stiffness research is Aircraft performance optimization via optimal induced drag control through artificial achievement of an elliptic aerodynamic load distribution for a whole wing with control surfaces by active aeroelastic inputs with novel controls
- Optimization of aeroelastic efficiencies η

$$\eta = \frac{\text{elastified aerodynamic forces (moments) in trimmed condition}}{\text{rigid aerodynamic forces (moments) in trimmed condition}}$$

(trimmed condition means the aircraft with controls is in normal force and pitch momentum equilibrium)

One idea of the sixties of the last century was concentrated on additional controls, i.e., for instance wing leading edge devices with defined attachment stiffness to minimize torsional deformation of swept wings and therefore optimize aerodynamic efficiencies. Another idea was to optimize the induced drag by introducing a jig shape of the wing to minimize aeroelastic wing torsion in cruise or other important manoeuvre flight conditions. One feasible principle of the variable active or semi active stiffness concept is based upon the selection of different stiffness for significant different flight conditions, for instance for low and high dynamic pressure or for subsonic and supersonic flight conditions by switching from one control surface- or wing attachment stiffness to another, or switching from one stringer/spar stiffness or actuator pressure to another with flight condition. The alternative principle by using actively controlled continuous variable stiffness with flight condition is not feasible due to complexity of structural design with nonlinear stiffness, and resulting aircraft safety problems. Actively controlled continuous variable stiffness can lead to elastic mode instabilities for the aircraft with and without flight control system (FCS), since variable stiffness leads to elastic mode frequency shifts and an elastic mode coupling phenomena (flutter). With the effect of FCS aeroservoelastic instabilities can also occur in case of continuous variable stiffness.

The design of variable stiffness concepts should consider only linear relationships of force displacements, i.e., linear stiffness and linear actuator force- displacement characteristics. Furthermore the design of active variable stiffness concepts shall be introduced after a passively optimized structural design. For example in the case of a large component design (Simpson and Schweiger 1998) at least the open loop modes of the system had to be held fairly constant as not to disturb the complete aircraft requirements for FCS design. Thus the constraint on mass and mass distribution of the active material (PZT wafer actuators) was optimized with the passive stiffening of their integration.

5.1. Active aeroelastic case

In Fig. 12 a static aeroelastic application (Schweiger and Simpson 1999) was realized by implementing various smart material actuators. At high dynamic pressures it was even possible to use PZT rod actuators to a positive extent. It is not possible in contrast without huge extra expense to use a parallel hydraulic lane. The smart materials in the low displacement amplitude range offer an excellent ratio between releasable potential strain energy and employed electric energy. One degree superimposed control surface deflection was the working range in the example, Fig. 12. Another example on the same lines for a variable stiffness actuation system was already used for the F/A-18E/F, see Flight International, January 20-26,1999, ‘Balanced Upgrade’. Here the hydraulic pressure switches from 207 bar to 345 bar (3000 to 5000 PSI) at high dynamic pressures to compensate aeroelastic losses. But it has to stated that hydraulic fluid potential energy storage is very inefficient compared to the strong pressure increase.

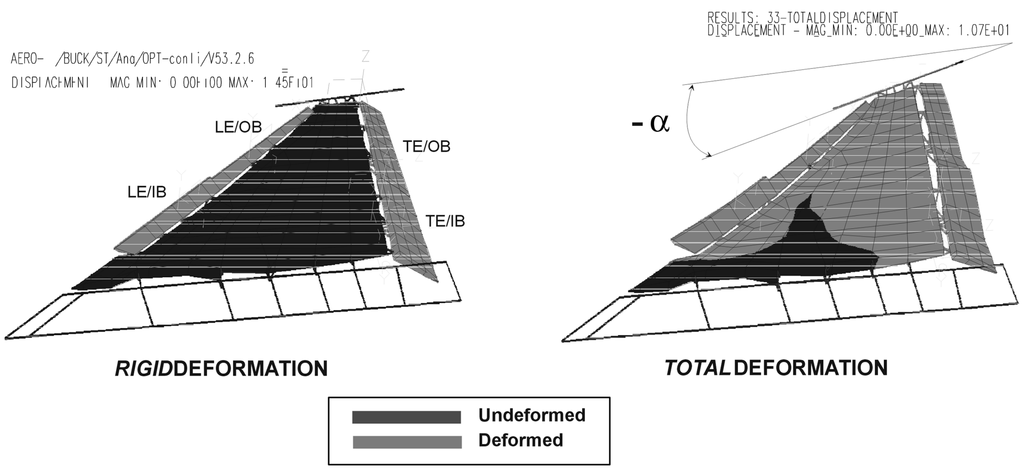

Fig. 12 Active Aeroelastic load supposition, one degree commanded warp feed back on a fighter aircraft wing with 4 smart actuators in-lane with classic hydraulics at Mach 1.2/102 kPa dynamic pressure, optimized under deformation and actuator penalty constraint, including buckling, in aero elastic equilibrium for maximum roll efficiency

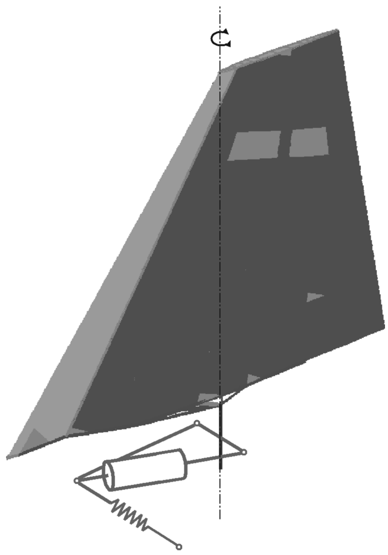

Fig. 13 All movable fighter aircraft fin study

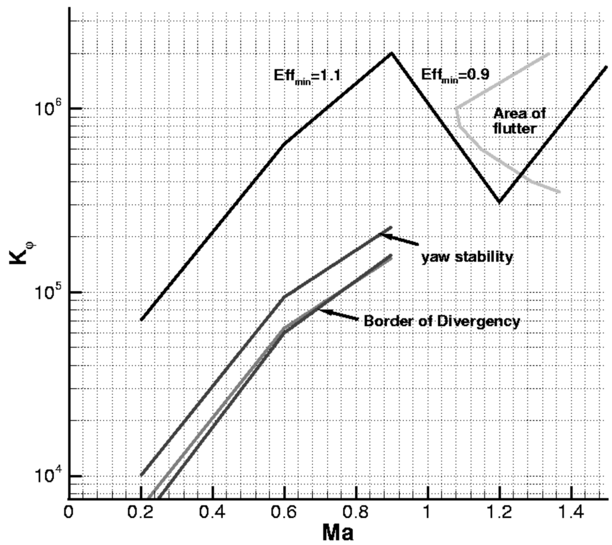

Fig. 14 Design envelope of all movable fin considering variable stiffness

An example of a semi active variable stiffness system for aero elastic enhancement on an all-movable vertical tail is described below. An active all-movable vertical tail (AMVT) design with increased effectiveness is possible with a variable attachment and variable actuation stiffness. This can be done mechanically, hydraulically or as a combination of both and also with for example variable stiffness with such systems based on MRF (Magneto Rheological Fluid) technology. The reason for considering an all-movable fin design is foremost, structurally speaking, reduced weight. An example of such a conceptual fin with basic actuation and variable spring ram effect is depicted in Fig. 13 There are advantages when designing for directional stability at higher dynamic pressure where much less weight penalty is incurred in providing efficiency losses, i.e. the aeroelastic efficiency of all-movable fin η dropping down in positive value to achieve an efficiency comparable to classic fixed fin with rudder, see the trend beyond Ma in Fig. 14. In previous real designs one search is also for a fixture axis design that suits the hinge moments at high speed. Additionally the question arises for stability for a variable stiffness add-on. Fig. 14 gives such a design envelope variable stiffness versus Mach Number.

The variable stiffness should be non safety critical and offer add-on benefits. Such benefits are allowable control efficiency gains at very low speeds. It is a case of philosophy whether one wants to penetrate artificially beyond minimal rigid control speed, but it is not compelling in order to gain an advantage.

6. Equipment vibration suppression systems

Adaptive shock mounts and vibration dampers were predicted to achieve a sustainable market within a very short period of time. Applications considered for these devices are mainly high precision electronic and optical equipment for which requirements (often according to military standards) and thus cost can be reduced if an adaptive load bearing device is able to decouple it from a harsh operational environment. Often these devices were considered to be piezoelectric actuators but it turned out that much more conventional solutions such as pneumatic or hydraulic systems are the much smarter solution, with piezoelectric elements working possibly on a more secondary level for serving within this pneumatic or hydraulic system. A pneumatic solution has been achieved successfully in hardware for damping electronic component off the shelf (COTS) that now allows this equipment to meet military specifications in flight it was not able to meet before.

In order for aircraft platforms to carry out their specific mission, equipment, so-called avionics is needed. In aeronautics one discerns between flight management and mission geared elements. Regarding functionality, it is still possible to subdivide further into a passive or active role. For example an optical sensor and a laser-inertia sensor provide an *active information for* flight and mission task performance, other installations provide computing and power management capabilities which constitute a *passive augmentation* of electronic information. Vibration is such a key physical disturbance which often precludes an “optimal” avionics integration solution. In the case of the more passive equipment, at least the effect on a desired quantifiable robustness is paramount. Because of cost and obsolescence pressures more use of readymade or component/commercial off the shelf solutions (COTS) is increasingly a fact of business. These systems may contain many unknowns concerning their physical stability, sometimes even a reliable tracing of standard qualification procedures is not even possible.

It is extremely difficult to control vibration levels at the equipment-aircraft structure interface if higher mass loads, by higher g-force, tighter manufacturing tolerances, higher data flow stability needs and higher performance with higher thermal loads prevail.

Because of the usual structural impedance conditions, treatments on the interior equipment electronic masses to reduce their vibration levels can be legitimate quick fixes, but these concepts lack in efficiency. They cannot subdue the mobility of the system at the equipment interfaces. Conversely, controlling the dynamic motion at the interface in the first place controls the boundary conditions strongly at the lesser mass electronic elements.

Smart materials and especially the “philosophy” of solid state (actuation) materials lend themselves to an integrated compensation concept. An active force-displacement output or energy harvesting and energy bleeding can be incorporated. The mechanical and electrical impedance which are coupled can

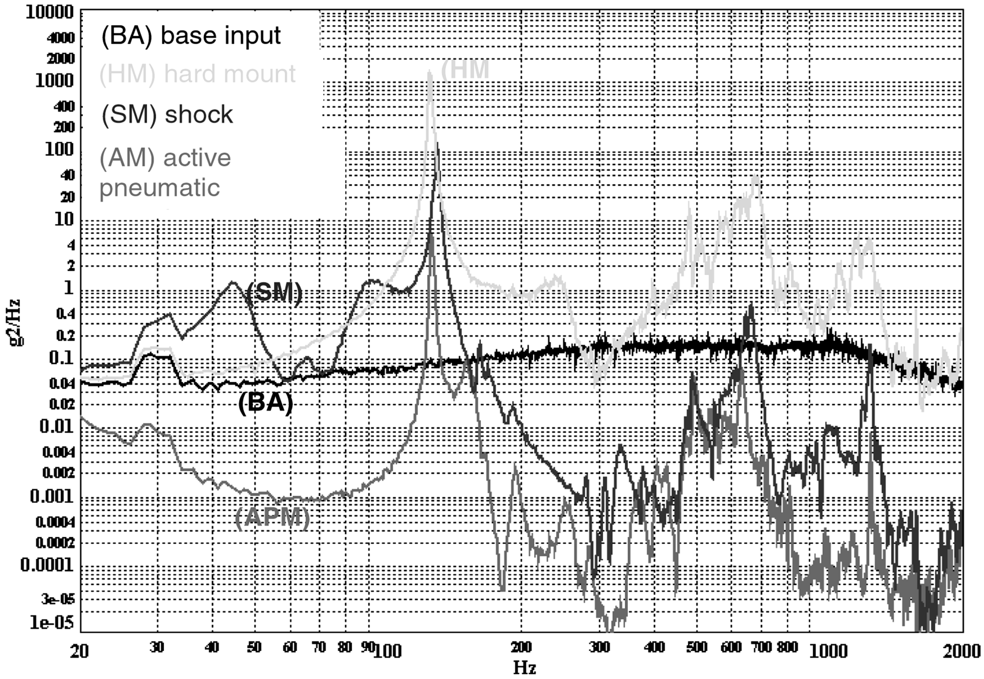

Fig. 15 Comparison by strategy of avionic mounting vibration isolation performance

be managed. A meagre competence in this respect is given by Perovskite materials, which are then deemed smart. The problem is that the active material state variable response (amplitudes and charge fluxes) lead often to impossible power and geometry design conditions.

The most convincing and affordable solutions in dealing with vibrations though seem to come from hybrid solutions evolving from visco-elastic mounts, pneumatic mounts with optimal support or adaptor structure. The intelligence used to make the hybrid solution smart systems from the logic based on passive variation of material impedance, pneumatic logic and/or a certain degree of electronic control. The advantages being found in shock , acceleration, velocity and displacement responses with the option to fall back on a system with no active energy requirement at all, or get out of the electro magnetic compatibility (EMC) design trap. Known failure modes and maintenance technology can be assumed.

An example of performance is shown in Fig. 15 comparing a hard mount (HM), a viscous-elastic shock mount (SM) and an active pneumatic mounting (APM) concept, depicting the power spectral density (PSD) acceleration response of a printed circuit board dummy within an avionic box. This PSD is traced, with the base acceleration (BA) imposed at the respective mount interface. The base acceleration is a compromise or generic condition related to high performance aircraft exhibiting considerable low and higher frequency disturbances. The peak at roughly 125 Hz exemplifies the problem that *even at lower disturbances severe manifestations of energy concentration at electronic parts are always to be expected.* The shock mount (SM) and active mount (AM) offer an alleviation of the vibration levels, whereby the active mounting is the most superior solution. For instance the low frequency inputs are additionally mitigated, which is important for special airframe responses like buffeting, gun fire, stores departure and other transient impacts.

Up to now practical efforts have concentrated on HM and SM solutions. The proportion of investment in basic SM solutions has been growing, which necessitates already a high level of material technology expertise, discerning the appropriate in service life performance. The SM shall be cheap and replaceable, the supported avionics attaining more safety and predictability per cost investment. This is philosophically different to a unified common passive avionic structure strategy with an aimed for 25 years continual robustness for equipment and mount.

The active mount concept, also containing sacrificial elements, offers on top of that an even more predictable and more controllable boundary condition. In the case of sensors one needs special efforts that generally preclude pure SM solutions. A lot depends on the active avionic element requirement. Some problems and solutions are discussed in Simpson (2001). Semi-active control, e.g., switching of mount material compliance, is one growing popular option. Otherwise, special auxiliary oscillating systems may be added on to burn off energy or at least store and release energy in a controlled manner. This option can be a modern tuned mass damper. This is less inhibitive to the avionic product than sole polymer treatments (free layer/volume, constrained bonding) directly on the electronic parts.

Through pneumatic solutions though, a clean and thermally clever balance in the system can be achieved. The accrued heat in the working fluid can be simply dumped, i.e. by active refilling of air. The strategy presently is to devise self-levelling and importantly self precision assembly for the equipment, but with no active coupling at high frequency.

This is an answer to the reality of available controller & amplifier solutions and material effects at high frequencies. Additionally, the supporting secondary structure and sacrificial elements must undergo optimization. If the dynamic stiffness of the secondary structure, e.g. shelf, is too low then there is nothing one can do.

Furthermore, the self-levelling capability of a pneumatic solution must be made adaptable to the envisaged aircraft platform g- manoeuvre loading amplitude and loading rate functions, also towards innate aircraft platform stability sensitive frequencies. Such design tasks were carried out in various European Framework project research efforts, e.g., VIBRANT (vibration reduction by active control technology). The hardware is now at a high technology readiness. The best solutions have been flight tested and qualified on various flight platforms, e.g., Simpson (2004).

For most flying aircraft, one will try to get by with passive mount solutions, i.e. application of HM and SM, as long as the cost and simultaneous avionic performance increases don't overwhelm the available retrofit boundary conditions. Even for this case more knowledge on smart material implementation is needed to keep up aircraft competitiveness, which relies on controlled avionic performance under vibration under combined loads. Adaptive mounting, because of cost and obsolescence of systems, seems now a more competitive solution. The adaptive mounting insists a low constant vibration condition, thus pre-empting costly re-qualification efforts. Fig. 16 shows how a weak COTS equipment robustness (intermediate curve) is made acceptable under a harsher Military vibration envelope load, (top curve), because the adaptive mounting ensured the strongly reduced vibration levels (lowest curve). For new aircraft concepts, solutions depend on the aircraft performance specification. It is not clear without specific research whether a fully active solution with more power consumption can be avoided for instance for some special remotely piloted vehicle operations.

7. Adaptive airframe vibration suppression systems

The availability of shape memory alloys (SMA) or piezoelectric actuators and motors has stimulated

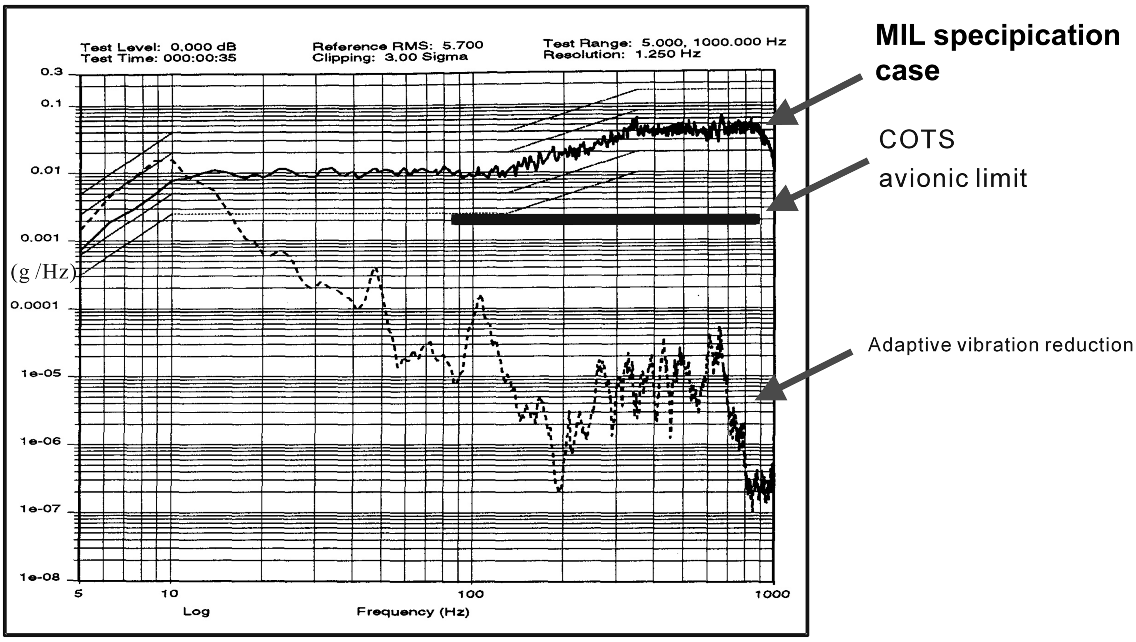

Fig. 16 Practical integration case using adaptive mounting to protect COTS avionic equipment

the discussion of adaptive wings with respect to vibration and flutter control. Specifically the problem of fin buffeting has been very much considered. In a study in which different smart and conventional concepts on how to alleviate buffeting of a fin of the size of the Euro fighter Typhoon were analyzed, a conventional concept with an additional rudder turned out to be a more promising concept than any concept with a single localized or a variety of distributed piezoelectric actuators around the fin (Dürr, *et al*. 1999, Kaiser, *et al.* 1999), the concept of piezoelectric actuators that activates a small trailing edge flap has however shown to be quite successful with helicopter rotor blades regarding improvement of the lead-lag damping. Again an additional flap is the solution to the problem but here the smaller size of the flap allows it to be driven by a piezoelectric actuator compared to the much larger additional rudder for the fighter, where only a conventional hydraulic system can help.

Another option is the integration of SMA wires into composite materials which requires a good understanding of the SMA-composite's behaviour as well as the manufacturing implications. This was extensively studied in a EU-funded project which ended in 2001 and where a 0.5 m tall fin was built, of which the skins were made out of a SMA-composite while the ribs, spars, leading and trailing edge were made from aluminium. Manufacturability was proven as well as performance where the latter led to a change in the fin's normal mode frequency when heating up the SMA wires resulting in enhanced flutter performance by relatively simple means. In some other more materials related testing, improvement in damping by up to a factor of 3 was shown when integrating of few volume % of pre-strained SMA-wires into the composite.

Buffeting is an aero elastic phenomenon occurring on various high performance fighter aircraft. 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. In the early 90s active systems for fin buffeting alleviation were suggested and analyzed in the literature. 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 fighter aircraft tails a joint research program in the field of advanced aircraft structures was initiated between DaimlerChrysler Military Aircraft Division, DaimlerChrysler Research and Technology and the German Aerospace Centre (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, a piezo-interface concept was studied in collaboration with DLR while a concept with structurally integrated piezo-ceramic actuators was realized in collaboration with DaimlerChrysler Research and Technology, (Becker and Luber 1998, Becker 2002, Dürr, *et al*. 1999, 2000). 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.

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-18 fighter aircraft. In addition to theoretical assessments, wind tunnel tests on a 1/6-scale model of an F-18 were conducted at NASA Langley. The project culminated in a full-scale ground test on an actual F-18 fin performed at the Aeronautical and Maritime Research Laboratory (AMRL) in Melbourne.

The benefits/deficits could be demonstrated for 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 (Dürr, *et al*. 2000, Stüwing, *et al*. 1999). Also wind tunnel tests on a fighter aircraft model have been performed by the Technical University of Munich (TUM) to demonstrate the effectiveness of the vibration alleviation of the active auxiliary rudder (Breitsamter 1999, 2000). 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 could be demonstrated (Dittrich, *et al*. 1999, Dürr, *et al*. 1999, 2000, Stüwing, *et al*. 1999). In addition the maturity of system integration into the total aircraft system has been evaluated.

For all concepts an investigation and comparison has been 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. The total aircraft structural dynamic model as well the unsteady aerodynamic modelling which was applied for the comparison study has been updated based on ground test results as well as on flight test results and in one case on wind tunnel results (Breitsamter and Laschka 2000). 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.

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 (Manser, *et al.* 1999).

8. Unmanned aerial vehicles

Trials to apply piezo-electrics or SMA for the actuation of control surfaces of conventional types of manned aircraft, have not shown to be too successful, see (Dittrich 1994). It is more the smaller control surfaces where these ways of piezoelectric and SMA actuation have been more seriously discussed. With regard to future applications unmanned aerial vehicles (UAV) may be the platform where this type of actuation can however be of very specific interest. UAV's, the new emerging field in aerospace, deals with aircraft of a size where the aerodynamic profiles and control surfaces are indeed in a range where the smart technologies described before have shown to be promising, see (Dittrich 2000). Furthermore UAV's still possess a larger freedom in design since some of their design issues have either not been sufficiently solved or may still not have been standardized such that alternative solutions may still be of great interest. In excess of the few sensing and actuation applications mentioned above there is a large amount of further smart structures applications to go with UAV's. MEMS is one of them where gyroscopes have been developed and are available off the shelf, which may be used for a variety of flight control applications. Other applications can be related to smart antennas where feasibility has been shown with a variety of laboratory samples which may not need to be scaled up in case they would be applied to UAV's.

9. Conclusions

Keeping in mind that each significant technology easily takes 25 to 50 years to fully mature, achievements related to smart materials and structures in aerospace has not to be considered to be too bad at present.

The sensing aspect in the context of *Structural Health Monitoring – Manufacture Monitoring* is fully applicable even to existing conventional structures and is ready to go through the certification process once benefits are clearly quantified and recognized, and the most suitable sensing solution is determined.

Electromagnetic Structures for radomes, the introduction of wide frequency band sensors and the integration of multiple sensors under one radome has resulted in the requirement for increased broadband performance and low observable, mechanical loads, temperature, lightning strike or bird impact requirements The present solutions are quite complex multilayer structures (generally made out of composite or ceramic materials) combined with frequency selective surfaces (FSS). Especially FSS, layers with periodic radiating elements (either metallic antenna elements on a dielectric substrate or dielectric slots in a metallic layer) have proven to be a powerful tool to tailor the transmission spectrum of a structure.

Electromagnetic Structures like structurally integrated antennas incorporated into the primary structure skin of an airframe are part of the load carrying structure. The extra weight of the antenna integration is considerably reduced while preserving the aerodynamic efficiency of conformal antennas and offers additional surface areas on the airframe available for antenna integration, like the surface of tank structures. From an low observability (LO) point of view, the integration into the structure eases the LO design, as the number of electromagnetic interfaces is reduced, decreasing the number of secondary scattering centres.

Controllable Electromagnetic Structures i.e. tunable radar absorbers have been developed on the basis of multilayer structure with an integrated network of PIN diodes.

Wind tunnel results and aeroelastic simulations for *Semi Active and Active Aerodynamic and Shape/ Contour Control* demonstrate and validate the benefits with respect to manoeuvre performance, drag reduction, enhancement of aircraft manoeuvre control and aircraft stabilization at low speed. At high dynamic pressure the improvements might reduce due to aeroelastic effects. However as demonstrated by aeroelastic simulations there are still significant benefits available at high dynamic pressure. Structural concepts for shape/contour control and control mechanism shall therefore developed with priority.

Regarding actuation of systems using Active and Semi Active Variable Stiffness, there are opportunities around but these can not be seen by simply replacing the conventional by the smart actuator. Smart actuators show their strength when it comes to actuation of smaller sized components. Keeping therefore the vision of the adaptive wing with structure integrated sensors and actuators alive, the solution can only be seen with aircraft of a size smaller than the ones produced today.

The most convincing and affordable solutions in dealing with *Equipment Vibration Suppression Systems* seem to come from hybrid solutions evolving from visco-elastic mounts, pneumatic mounts with optimal support or adaptor structure. The intelligence used to make the hybrid solution smart systems from the logic based on passive variation of material impedance, pneumatic logic and/or a certain degree of electronic control.

Based on the results of the research effort on active vibration and buffeting alleviation systems for fighter aircraft the following recommendations are made for *Adaptive Airframe Vibration Suppression Systems*: A demonstrator program to show the alleviation of the separated flow induced fin vibrations could be implemented immediately for the proposed rudder concept by including the lateral phase stability concept into the current flight control system without any modifications to the fin. The auxiliary rudder, piezo- interface and distributed piezoelectric actuator concepts have all exhibited considerable promise for the active suppression of fin buffet alleviation at large angles of attack. A demonstrator program employing one or more of these concepts was proposed to show their viability for buffet-induced fin vibrations in flight tests. A decision on the system(s) to implemented on an actual aircraft has then to made based upon the complete test and analysis results. (Intermediate-term recommendation). If buffet-induced fin vibration loads become larger with angles of attack, then one of the active buffet-load alleviation concepts could be implemented. The technologies developed in the context of buffet load alleviation should be transferred into future military aircraft concepts – such as for instance *Unmanned Aerial Vehicles* (*UAV's*) – as well as to civilian aircraft and helicopters for active vibration suppression systems. 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 available larger active strains – 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.

Unmanned Aerial Vehicles - UAV's may allow smart materials and structures to find their way into future application.

References

Becker, J. and Luber, W. G. (1998), "Comparison of piezoelectric systems and aerodynamic systems for aircraft vibration alleviation", *Proceedings of SPIE*, **3326**, 13-27.

Becker, J., Schröder, W., Dittrich, K., Bauer, E. J. and Zippold, H. (1999), "The advanced aircraft structures program - an overview", *Proceedings of SPIE*, **3674**, 2-13.

Becker, J. (2002), "Active buffeting vibration alleviation - demonstration of intelligent aircraft structure for vibration & dynamic load alleviation", *ESF-NSF Workshop on Sensor Technologies and Intelligent Structure*, Como, Italy.

Berchtold, G., *et al.* (2001), "Impact of electromagnetical structures on future air vehicles", Keynote, *Proceedings of the 10th European Electromagnetic Structures Conference (EESC)*, Munich, Germany.

Breitsamter, Ch. (1999), "Aerodynamic active vibration control for single-fin buffeting alleviation", Deutscher Luft- und Raumfahrtkongress / DGLR Jahrestagung, Berlin, Germany.

Breitsamter, Ch. and Laschka, B. (2000), "Aerodynamic active control for EF-2000 fin buffet load alleviation", AIAA 2000-0656, 38th Aerospace Sciences Meeting Exhibit, Reno, NV., USA.

Breitsamter, Ch. (2003), "Aerodynamik hochmanoevrierfaehiger flugzeuge mit formvariablen hinterkantenklappen", DGLR-2003-126, Deutscher Luft- und Raumfahrtkongress, Muenchen, Germany.

Breitsamter, Ch. (2004), "Aerodynamic efficiency of high maneuverable aircraft applying adaptive wing trailing edge section", ICAS-2004-4.3.2, *24th Congress of the International Council of the Aeronautical Sciences*.

Dittrich, K. (1994), "Formveränderung von flügelstrukturen mittels integrierter shape memory alloy aktuatoren (Shape change of wing structures with integrated shape memory alloy actuators)", *Proceedings of the DGLR Conference*, Erlangen, Germany.

Dittrich, K. (1998), "Prospects of smart structures for future aircrafts", NATO Advanced Study Institute Mechanics of Composite Materials and Structures", Tróia, Portugal.

Dittrich, K., Simpson, J., Becker, J., Dürr, J. K., Floeth, E., Ihler, E., Herold-Schmidt, U. and Zaglauer, H. W. (1999), "Fin-buffet alleviation via distributed piezoelectric actuators: materials qualification program", *Proceedings of SPIE*, **3674**.

Dittrich, K. *et al.* (1999), "Structural health monitoring (Strukturueberwachung)", *Military technology symposium at WIWEB*, Erding, Germany.

Dittrich, K. (2000), "Structural concepts for future uninhabited combat aerial vehicles (UCAV)", *Proceedings of the RTO Conference on Unmanned Vehicles (UV) for Aerial, Ground and Naval Military Operations*, RTO Meeting proceedings MP-052, Ankara, Turkey.

Dittrich, K. *et al.* (2001), "Radar absorbing structure with integrated PIN diode network", *Proceedings of the 10th European Electromagnetic Structures Conference*, Munich, Germany.

Dittrich, K. *et al.* (2003), "In-flight measurement of acoustic background noise for the development of impact detection algorithms", *Proceedings of the SPIE NDE and Health Monitoring Conference*, Vol. 5046-37, San Diego, USA.

Dittrich, K., Becker, J. and Luber, W. (2004), "Structural concepts of morphing wing", *Third European Conference on Structural Control*, *3ECSC*, Vienna University of Technology, Vienna, Austria.

Dürr, J. K., Floeth, E., Herold-Schmidt, U., Ihler, E., Zaglauer, H. W., Becker, J., Dittrich, K., Manser, R. and Simpson, J. (1999), "Fin-buffet alleviation via distributed piezoelectric actuators: materials qualification program and full-scale demonstrator tests", *Proc. Adaptronic Congress*, Potsdam, Germany.

Dürr, J. K., Krohn, N., Nixdorf, K., Lütze, S., Herold-Schmidt, U. and Busse, G. (1999), "Non-destructive testing of surface bonded piezoelectric patch actuators", *Proceedings of SPIE*, **3674**.

Dürr, J. K., Herold-Schmidt, U., H. Zaglauer, H. and Becker, J. (2000), "Active fin-buffeting alleviation for fighter aircraft", *RTO Structure & Materials Conference Braunschweig*, Germany.

Kaiser, S., Melcher, J., Breitbach, E. J. and Sachau, D. (1999), "Structural dynamic health monitoring of adaptive CFRP structures", *Proceedings of SPIE*, **3674**, 51-60.

Kress, K.-P. *et al.* (2001), "Smart wide-area imaging sensor system (SWISS)", *Proceedings of the SPIE Smart Structures and Materials Conference*, Vol. 4332, Newport Beach, USA.

Kress, K.-P. *et al.* (2002), "Imaging ultrasonic sensor system SWISS completed 60000 simulated flight hours to check structural integrity of aircraft subcomponent", *Proceedings of the SPIE NDE and Health Monitoring Conference*, Vol. 5046-39, San Diego, USA.

Kress, K.-P., *et al*. (2003), "Integrated imaging ultrasound (SWISS)", *International Workshop on Structural Health Monitoring*, Stanford 2003, USA.

Kress, K.-P. *et al*. (2003), "Overview on the AHMOS project", *International Workshop on Structural Health Monitoring*, Keynote, Stanford, USA.

Manser, R., Simpson, J., Becker, J., Dürr, J. K., Floeth, E., Herold-Schmidt, U., Stark, H. and Zaglauer, H. W. (1999), "Fin-buffet alleviation via distributed piezoelectric actuators: full-scale demonstrator tests", *Procceedings of SPIE,* **3674**, 13-21.

Schweiger, J. and Simpson J. (1999), "Needs for analysis and integrated design optimization of active and passive structure for active aeroelastic wings", *SPIE's 6th Annual International Symposium* "Smart Structures and Materials", Newport Beach, California, CA, USA.

Simpson, J., Schweiger, J. (1998), "Industrial approach to piezoelectric damping of large fighter aircraft components", *Proceedings of SPIE*, **3326**, 34-47.

Simpson, J. (2001), "Current approaches to reduce structural dynamic impacts on the performance of aircraft mounted sensor systems", *International Forum on Aeroelasticity and Structural Dynamics*, Madrid, Spain.

Simpson, J. *et al.* (2004), "Aktive Lagerung für Avionik Integration und Erprobung", *Adaptronic Congress*, Hildesheim, Germany.

Stüwing, M., Sachau, D. and Breitbach, E. J. (1999), "Adaptive vibration damping of fin structures", *Procceedings of SPIE,* **3674**, 31-39.

CC