Smart Structures: Recent Developments within Aeronautics Applications (Invited Review)

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Abstract:
Smart structures influence the elastomechanical behaviour in a wanted way by optimally integrated actuators and sensors to realize morphing, active vibration reduction, active structural acoustic control and structural health monitoring. Especially in aeronautics large progress can be observed, meaning that the lab stage has been passed and high TRL levels are reached. Challenges for harsh environmental conditions involving lightning strike, bird impact and icing, just to name a few, have to be overcome. Also integrational aspects of actuators and sensors play a major role to realize lightweight and producible smart structure like morphing droop noses, actively twisted rotor blades, smart linings or CFRP fuselages with integrated structural health monitoring. This review gives an overview of some recent applications within aeronautics which involve full-scale demonstration and wind tunnel testing of smart structures as well as an outlook for further developments.

Keywords: Morphing, Adaptive Wing, Smart Droop Nose, Active Twist, ASAC, Active Structural Acoustic Control, Smart Lining, SHM, Structural Health Monitoring, Smart Structures

Introduction

The challenging long-term targets formulated in the ACARE research agendas (75% reduction in CO2 emissions, 90% reduction in NOx emissions and 65% reduction of the perceived noise in reference to narrow body engine performance of year 2000 are envisaged up to 2050) have motivated the introduction of new technologies like smart structures into aeronautics applications in the past 10 years [1], [2]. National and European funding has strongly supported this development. Smart structures have great potential in aeronautics since they allow a structure to actively influence its elastomechanical behaviour. This way morphing, active vibration reduction, active structural acoustic control and structural health monitoring can be realised. Morphing structures have especially been boosted by the European projects SADE, CHANGE, NOVEMOR, Clean Sky I-SFWA and SARISTU. The *smart morphing droop nose* is one major result of these efforts and illustrates the development from basic research to an industrial level of maturity in an impressive way. Highly dynamic morphing for helicopter rotor blades has intensively been investigated within the European projects FRIENDCOPTER and Clean Sky I-GRC. *Actively twisted rotor blades* with integrated piezoceramic actuators have proven to master this challenging task both structurally and aerodynamically. Strategies for active structural acoustic control, better known as ASAC, could be demonstrated within the national projects SYLVIA and DIANA. A *smart lining* based on a lining structure of an aircraft's interior from the shelf could be demonstrated to reduce broadband and multi tonal noise but also in parallel to be used as replacement for loudspeakers. Finally for *structural health monitoring* systems the level of maturity was lifted to another step within the European Project SARISTU. A full scale CFRP fuselage structure with integrated actuators and sensors proved the feasibility of the Lamb wave based approach. These are some outstanding examples for recent developments of smart structures within aeronautics which will be illustrated in the following sections.

Actively twisted rotor blades

The complex unsteady aerodynamic conditions on helicopter main rotors cause vibration and noise in and around rotary wing aircrafts. One way of working against those is the use of individual blade control to increase the miss distance between vortexes and blades – a major reason for most of the noise. Most prominent technologies to support individual blade control are blade flaps, and active pitch links to introduce control inputs. An effective way, which does not generate additional vortexes, is active blade twist. The basic principle to derive tip twist (φ) on a blade of the length l is the implementation of piezoceramic actuators in a way that a twist momentum (M_t) is being generated, which is working against the torsional rigidity (GI) of the blade.

$$\frac{\varphi}{l} = \frac{M_t}{GI} \qquad (1)$$

Several different methods that introduce such twist into a blade can be found in literature [3] and [4]. The reason for the use of piezoelectric actuators is their quick response which allows actuation even at higher harmonics of model rotors, which requires sinusoidal excitation at up to 60 Hz. Among those are concepts utilizing stack type actuators in combination with a tension torsion coupling by DLR. The tension in the skin – resulting from the centrifugal load – is being altered by the actuator leading to changing levels of tension as well as torsion. A concept by ONERA proposes a slotted airfoil, which is closed by an actuator. This concept is introducing warping, which will directly lead to twist. The most promising concept is the integration of skin integrated actuators. The basic principle is shown in Fig. 1, an example of a blade set in Fig. 2.

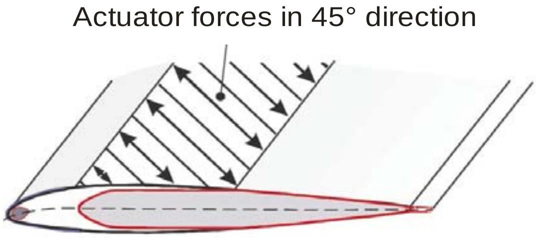

Fig. 1: *Working principle of active twist rotor blades*

In the blade skin there are actuators integrated with an actuation direction of 45° towards the rotor radius. The introduced forces lead to a shear which leads to a blade twist. Different combinations of actuators with orthotropic skins have been designed and demonstrated in the literature. It could be shown, that the combination of these actuators with pure helically aligned fibres – about 90° towards the actuator direction – in the blade lead to maximum twist. Besides the optimisation towards maximum twist at a desirable stiffness and eigenfrequency, a lot of care has to be taken in meeting other boundary conditions like location of the centre of gravity (*cg*), location of the *tension centre* and structural *strength*. These conditions are discussed in the following:

The *cg* of a rotor blade has to be at ¼ of the chord length. This is due to the fact, that aerodynamic lift can be subsumed there. A *cg* behind this point will lead to an instable blade which will tend to flutter in a wind tunnel. Since the actuators bring a major fraction of the weight and they are evenly distributed between the leading and trailing edge, there is a high demand on counter mass in the leading edge of the blade, which adds additional mass to the blade. Both of these effects can add up to as much as 35 % increased weight. That is why weight has to be taken into account during the design.

The *tension centre* is describing the location where an acting radial load will not lead to any lead-lag bending. The distance between *gc* and *tension center* is to be kept as small as possible in order to keep the blade from bending in lead-lag direction, which would lead to high strains especially in the trailing edge.

The *strength* of the blade is mainly limited by the strength of the actuators. The design has to make sure that strain levels in the actuators are not succeeding the allowable. In the case of MFC the manufacturer gives the max. operational tensile strain as < 4500 ppm.

Fig. 2: *Blade set of active twist blades by DLR*

All these considerations have to be taken into account for a proper blade design, which allows the incorporation of a sensitive and brittle actuator like a piezo actuator into a harsh environment like a helicopter rotor blade, where accelerations far beyond 1000 g are acting on the actuators.

A recent development is the implementation of low voltage actuators in a rotor blade [5], investigated in the European project Clean Sky I – Green Rotorcraft. This is dramatically reducing the voltage needed by the actuator from currently 1500 V down to 120 V.

The key to the success of this technology is still the suitable implementation of the sensitive actuator material into the structure.

Smart morphing droop nose

The development of the smart leading edge technology started with conceptual studies on the feasibility of selected patents and concepts in the DLR-project LEISA (Low noise exposing integrated design for start and approach) [3]. It was found that the smart leading edge droop nose device could be used for noise reduction in approach if a maximum lift comparable to a slat could be realized. First weight estimation indicated a weight comparable to a wing with slats. The investigations continued with the national R&T project SmartLED (Smart Leading Edge Devices) [7], [8], [9] and the European project SADE [10], [11], [12], [13] in which a static ground test and a low-speed wind tunnel test were conducted.

The objective of the SmartLED project was the verification of the feasibility for design, manufacturing and functionality with consideration of wing bending. Afterwards the compliance of structural deformations with aerodynamic requirements was checked in the 2D full-scale wind tunnel test in the SADE project. Within the European follow on projects (Cleansky JTI-Smart Fixed Wing Aircraft and SARISTU - Smart Intelligent Aircraft Structures) the smart droop nose was matured with respect to industrial aspects like impact protection, lightning strike protection, de-icing functionality and bird strike protection.

Fig. 3: *Large scale ground test of the enhanced adaptive droop nose.*

In parallel research activities focused on more fundamental topics like innovative morphing skin design and the application of topology optimized compliant mechanisms were started in other European and national projects (NOVEMOR – Novel Air VEhicle Configurations: From Fluttering Wings to MORphing Flight, CHANGE - Combined morphing assessment software using flight envelope data and mission based morphing prototype wing development, CRC880 - Coordinated Research Center 88o: Fundamentals of High Lift for Future Civil Aircraft). Despite the investigations in the SARISTU project [14] all previous research activities were based on the DLR F15/FNG- model geometry. As a major milestone in the development of this technology is the low speed wind tunnel test of the morphing leading edge model developed in the project SADE represents a leap in the technology readiness level of this high-lift concept. Here it was demonstrated that a morphing leading edge with given aerodynamic target shapes can be realized with fulfilling all relevant stiffness and strength requirements.

However, the integration of additional functionalities was required for increased technology readiness and application in aircrafts. In the European project SARISTU the objective was therefore the integration of erosion protection, lightning strike protection, de-icing functionality and bird strike protection without impacting negatively the morphing capability. While the first three could be realized by integrating functional layers into the basis laminate, the bird strike protection was realized by a standalone bird strike protection structure.

Together with the Airbus Group Innovations (Germany), Invent GmbH (Germany), Sonaca (Belgium) and VZLU (Czech R.) an integrated leading edge was developed and demonstrated in a wind tunnel as well as ground demonstrators. In a large scale ground test a 4m leading section was tested under wing bending and in combination with the integrated IPS (ice protection system) in static and fatigue tests (see Fig. 3).

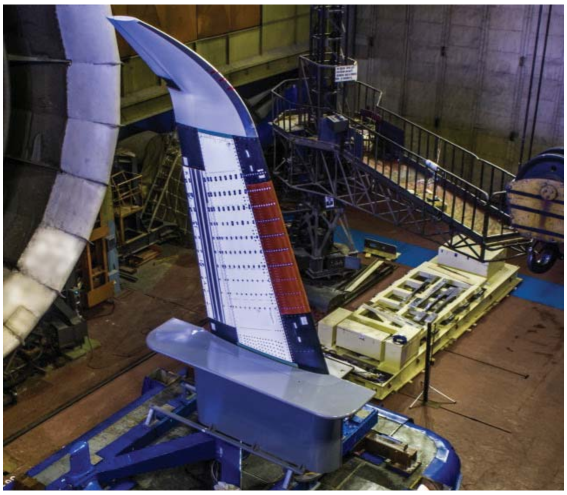

Fig. 4: *Smart leading edge integrated in the outboard wing demonstrator.*

The performance under relevant aerodynamic loading was tested in a large scale wind tunnel test (see Fig. 4) at the T104 at TsAGI facilities with a maximum speed of 120m/s. The performance of the bird strike protection structure was tested in corresponding bird strike tests.

Smart linings

Sidewall and ceiling panels are aircraft interior parts with low mass and high stiffness. This has a negative impact on the sound transmission loss of these structures especially at low frequencies. As a consequence, the level of interior noise and the passenger annoyance increases. External disturbance sources with a strong influence on interior noise are the engines and the turbulent boundary layer that surrounds the aircraft [15]. Classical soundproofing requires the use of additional mass and volume and hence leads to a heavier and less spacious aircraft. This, of course, is highly inefficient and undesirable. The smart-lining-technology follows an alternative approach which is able to reduce interior noise without an increase of mass and volume (see Fig. 5).

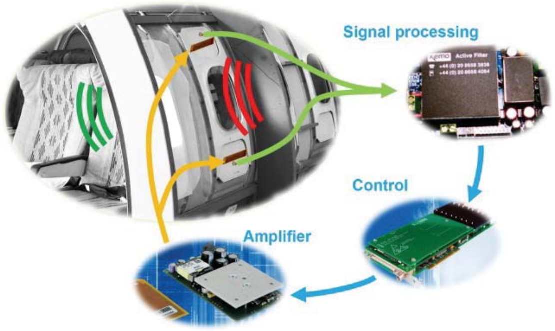

Fig. 5: *Principle of the active cabin noise reduction with smart linings.*

This is accomplished by the active reduction of noise emitting vibrations of the sidewall and ceiling panels (see Fig. 6). The integration of sensors, actuators and signal processing into a panel leads to a smart structure which is able to influence the acoustics in the cabin in a positive way [16].

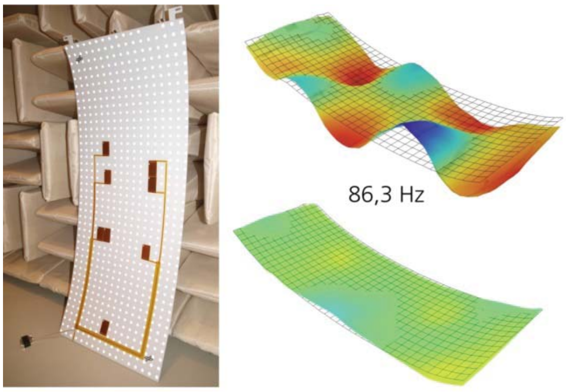

Fig. 6: *Smart-lining-demonstrator with piezoelectric transducers applied and wired (left) and reduction of acoustically relevant vibration by the active system (right).*

Such a smart panel is modular and can be used flexibly in the cabin since it requires only a power supply. A smart lining module could even provide additional features such as passenger announcement or in-flight entertainment and hence could replace classical loudspeaker systems.

DLR has conducted and contributed to several research projects related to the topic of active reduction of aircraft interior noise with smart panels. The first demonstrator of a smart lining was designed and built in 2011 within the framework of the LuFo-project SINTEG (funded by BMWi). This prototype, which is shown in Fig. 6, was tested in a sound transmission loss facility under broadband excitation. The smart lining was mounted to a carbon fibre reinforced plastic (CFRP) fuselage structure to implement an aircraft typical double panel configuration. Measurement results of the smart lining proved a significant increase of the transmission loss at low frequencies (< 500 Hz). A sound power reduction of up to 8 dB(A) was achieved in third octave bands by the active control (compared to the de-activated smart lining). The promising results motivated the continuation and intensification of research on smart linings. The more recent LuFo-projects DIANA and SYLVIA (funded by BMWi) concentrate on the development of a smart lining for the Airbus A350. Research is done in cooperation with the company DIEHL Aircabin which produces the Airbus interior parts.

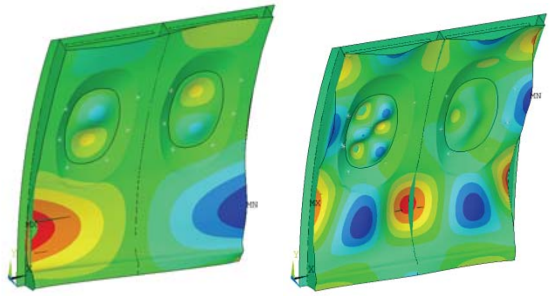

Fig. 7: *Simulated mode shapes of the coupled fuselage lining system at 48 Hz (left) and at 134 Hz (right).*

Fig. 7 shows the mode shapes of the coupled vibro-acoustic system at two eigenfrequencies. The simulation model will be used for the identification of dominant sound transmission paths and for the derivation of suitable transducer configurations for the active control system. The next steps are the manufacturing of the fuselage part and the mounting of the double panel system in the sound transmission loss facility of DLR. Measurement results will be used for model updating and validation. Different smart lining configurations will be derived and evaluated regarding control performance, robustness and weight and volume requirements. The main goal is the proof of concept of the smart lining technology for a modern serial production sidewall panel.

Structural Health Monitoring

Structural Health Monitoring (SHM) based on Lamb waves, a type of ultrasonic guided waves, is a promising method for in-service inspection of composite structures. Lamb waves can be excited and received using a network of actuators and sensors, which are permanently attached on the structure. By analysing the sensor signals, different kinds of structural defects can be detected and located through the interaction of the Lamb waves. The aim of the present work is to prove the damage detection and localization in complex and full-scale aircraft composite structures. Furthermore, a sensor network and manufacturing process is developed in order to integrate the SHM network into the manufacturing process of the structure (co-bonding) and to reduce the manufacturing and assembly efforts/costs. As aircraft structure, the door surround panel is chosen because of its high impact probability during aircraft operation and its high structural complexity. The design is based on civil composite aircraft structures. The structure exhibits a length of 5.1m, a width of 3.5m and a radius of approx. 3m.

As actuators and sensors piezoelectric transducers are commonly used for Lamb wave based SHM. The transducers are applied on the inner surface of the skin and arranged in form of arrays. The array consists of piezocomposites (DuraAct technology) to increase the reliability of the SHM system [17], [18]. Each piezocomposite is connected by thin cables with a stranded core. This cable type is chosen because it can tolerate high strain levels. As shown in Fig. 8, the piezocomposites as well as the cables are embedded into an unvulcanised EPDM (Ethylene Propylene Diene Monomer). The EPDM holds the piezocomposites and the cables in place and is an elastic protection from the environment.

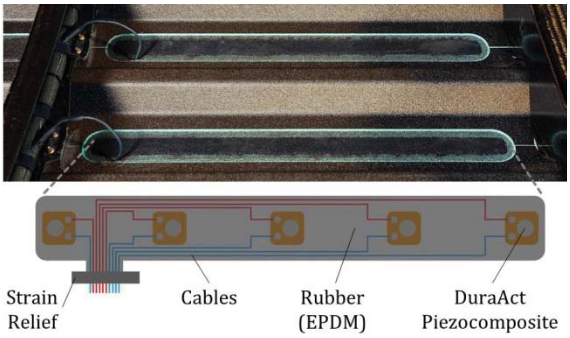

Fig. 8: *SHM array consisting of piezocomposite and cables embedded into rubber (EPDM)*

The skin is made from CFRP prepreg material and is laid-up by an automated fibre placement (AFP) robot, as shown in Fig. 9. After the lay-up of the skin the sensor arrays are positioned and applied by hand (see Fig. 10). The position of each sensor array is displayed by a laser projector.

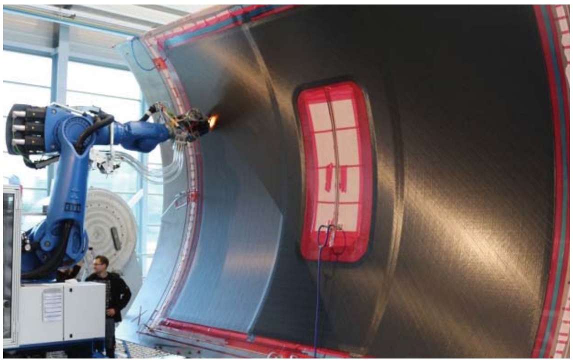

Fig. 9: *Skin lay-up by automated fibre placement*

In total, 126 arrays with 584 sensors are applied. The skin is cured together with the sensor arrays in an autoclave process at 180°C and 7bar.

Fig. 10: *Lay-up of SHM arrays on uncured skin*

After skin manufacturing the stringer are bonded on the skin using an epoxy film adhesive and cured in an autoclave process at 150°C and 3bar.

The final stage within the manufacturing of the door surround structure is the assembly of all components and the cabling of the SHM network (see Fig. 11). For the cabling of the SHM network, wiring harnesses with a specific length are pre-fabricated. After connecting the SHM arrays, it is proven that all 584 sensors survived the different manufacturing steps.

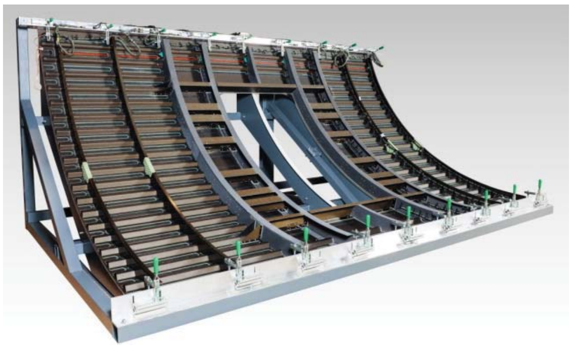

Fig. 11: *Manufactured door surround structure with integrated SHM network*

After the manufacturing and assembly baseline measurements of the SHM system are performed at different temperatures. Then 112 impacts up to energies of 130J are introduced using an impactor gas gun. After each impact the SHM system is activated to detect and locate the damage. It is proven that the SHM system is able to detect and locate the damages in complex and realistic aircraft structures.

The development and manufacturing of the door surround structure was carried out within the EU-project SARISTU together with the partners INVENT GmbH, FACC Operations GmbH and Airbus Group Innovations [19].

Conclusions

Smart structures have proven to have left the lab stage of basic research for certain applications within aeronautics. The examples of actively twisted rotor blades, smart morphing droop nose, smart linings and structural health monitoring systems shown in this paper represent some of the most recent and most advanced developments. High TRL levels are demonstrated by full scale tests. These developments have strongly been supported by large national and European projects like SADE, SARISTU, FRIENDCOPTER and SYLVIA. This also shows that the challenges of developing smart structures can only be tackled in interdisciplinary teams comprising experts from materials research, structural mechanics, aerodynamics, aeroelasticity, acoustics, flight mechanics, and systems engineering. Future goal will be a further maturation of the technologies. For the actively twisted rotor blades the next step will be the wind tunnel testing of a fully instrumented rotor blade. With respect to the smart morphing droop nose some flight tests are also under discussion. For the smart linings integrational aspects of sensors and actuators as well as the electronics have to be tackled next. Concerning structural health monitoring efficient contacting of the numerous actuators and sensors will further be improved. The progress made within the last years allows a justified optimism that these challenges can be overcome. Finally, smart structures for civil transport aircraft may become reality.

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