ACTUATOR DESIGN FOR A MORPHING HELICOPTER ROTOR BLADE

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ABSTRACT

Future helicopters will be improved with respect to external and cabin noise, vibration and performance. There is significant potential for improvement especially in forward flight which creates very different aerodynamic conditions on the rotor disc during each revolution.

A lot of research has been done during the last decades and several control concepts have been developed. To realize these concepts an appropriate actuation system is necessary. The most popular concepts so far have been the direct twist concept and the trailing edge flap.

A new, structurally more integrated actuation concept is the Active Trailing Edge, ATE. Actuator design and optimization for this concept are presented in this work.

1 INTRODUCTION

Today, helicopters still suffer from noise, vibrations, limited flight envelope and performance. Modern models already perform much better than early types. These improvements are mostly due to better rotor aerodynamics, novel planforms and airfoils, advanced tail rotor concepts, composite materials, hinge- and bearingless rotors, modern engines and passive vibration damping.

1.1 Noise

Main rotor, tail rotor and engines generate most of the external helicopter noise.

The acoustic signal of the main rotor consists of broadband and impulsive noise. The broadband sources are boundary layer flow effects on the rotor blades (so-called self noise) at high frequencies and blade interactions with turbulences in and about the wakes and tip vortices at medium frequencies. Blade-wake interaction (BWI) persists over a large range of operating conditions.

The low frequency impulsive sources are dominant especially in high speed forward flight and in descent flight, typical for landing. In descent flight or low speed maneuvers, the rotor blades encounter the tip vortices of preceding blades. This blade vortex interaction (BVI) causes loud slapping noises, dominating the acoustic signal of a helicopter. In high speed forward flight, the airflow at the blade tip becomes transonic. The occurring shock waves generate a loud noise directed in flight direction (high speed impulsive noise, HSI). Harmonic and higher harmonic loading noise are other low frequency sources at the main rotor. [1]

1.2 Vibration

Vibration sources in the helicopter are the main rotor, tail rotor, engines and other rotating systems as hydraulic pumps and air forces acting on the fuselage, e.g. tail shake.

Main rotor vibrations arise especially in forward flight. The rotor experiences varying fluid velocities and angles of attack at the advancing and retreating blade. Varying spanwise distributions of lift and drag excite the blade's bending modes. This results in alternating rotor hub loads, especially vertical forces and lateral and longitudinal mast moments. The occurring vibration frequencies are typically a multiple of the blade number and the revolution frequency [2]. Using more rotor blades and a small flapping hinge offset can help to reduce vibrations [3].

In high speed flight, vibrations can occur if the retreating blade suffers from strong dynamic stall while the advancing blade experiences transonic flow with the inherent shocks. Another source of vibrations is BVI especially in decent flight.

Deficient blade tracking can produce additional vibrations.

1.3 Higher Harmonic Control and Individual Blade Control

The main rotor is the main source of helicopter vibrations and noise especially in forward flight. Therefore, a technology for advanced rotor control can reduce both noise and vibration.

Higher harmonic control (HHC) aims on superimposing the standard blade pitch variation with an additional low amplitude blade pitch angle at multiples of the rotational frequency via the swashplate. Individual blade control (IBC) allows to control the pitch of each rotor blade independently. Both concepts allow to reduce vibration and BVI noise. IBC systems are better suitable for simultaneous vibration and noise reduction, shaft power reduction and a flight envelope extension [4].

1.4 Actuation systems

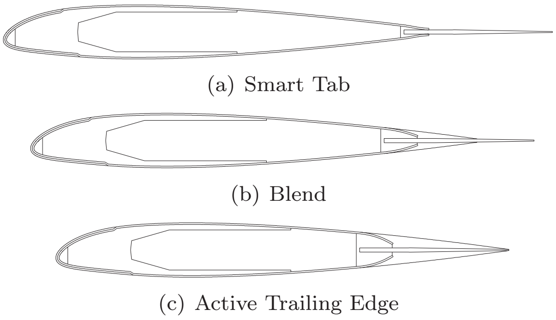
The conventional swashplate is not applicable to control each blade individually. Therefore, appropriate actuation systems are necessary. The first realized IBC projects featured hydraulic systems actuating the blade root. Actuation mechanisms based on active materials offer advantages in weight, power consumption and bandwidth [5]. The most advanced approaches so far are active twist control and trailing edge servo flaps.

Active twist varies the spanwise lift distribution without affecting the aerodynamic pitching moment. Blade twist is achieved by structure-borne twist actuation. Most of the presented twist concepts embed plies of piezo-electric fibres in the rotor blade's skin. The active fibres are arranged to induce strain at ±45° from the blade spanwise axis to generate a maximum twisting moment. Scaled rotors were tested in wind tunnels performing hover and forward flight using open and closed loop control [6]. A segment of an active twist blade in full-scale is presented in [7]. Main advantages of the active twist are the aerodynamically unchanged profile and the absence of moving parts.

Trailing edge flaps control the rotor blade dynamics via the servo effect. The change in aerodynamic pitching moment twists the rotor blade aeroelastically. Servo flaps have been developed in model-scale and full-scale. They usually apply piezo-ceramic stack actuators to drive the flap. A mechanical amplification of the active stroke is necessary. A helicopter equipped with trailing edge flaps was flight tested successfully by Eurocopter in 2005 [8, 9]. Figure 1 shows the BK117 in flight. Trailing edge flaps allow a modular design.

An electronic system comprising controller unit, power electronics, data acquisition and data and power transmission is necessary to operate piezo-electrical driven actuators.

Fig. 1 : BK117 equipped with servo flaps


(a) Smart Tab

(b) Blend

(c) Active Trailing Edge

Fig. 2 : Smart tab versus Active Trailing Edge

A new concept for an IBC actuator is the Active Trailing Edge, ATE. This paper presents the design and optimization of the ATE concept. All presented results are based on a generic Bo105 reference rotor with a NACA 23012 cross section.

2 ACTIVE TRAILING EDGE CONCEPT

The Active Trailing Edge concept realises a morphing cross section for a helicopter rotor-blade. The trailing edge of the airfoil is able to deflect upwards and downwards. Similar to the trailing edge flaps, the ATE aims to twist the blade aeroelastically using the servo effect. It can be looked at as a structurally more integrated servo flap. There are neither moving parts nor discrete hinges.

In the beginning of the project, two different layouts of a morphing cross section were regarded. Both of them employ a three-layer (trimorph) bender made up of piezo-ceramic actuators and a glass-fibre reinforced plastic core:

Smart Tab: The bending actuator is attached to the trailing edge of the baseline airfoil, see Fig. 2(a).

Active Trailing Edge: The bending actuator is completely integrated into the airfoil's trailing edge without changing its aerodynamic shape in neutral position, see Fig. 2(c).

A blend of the two alternative concepts is possible, see Fig. 2(b). First calculations revealed some advantages for both layouts. The Smart Tab has got a longer leverage to the rotor blade's neutral axis at 25% chord. Therefore, it can achieve a higher aerodynamic moment for the same deflection of the actuator. For the same reason, more additional mass is necessary to balance the centre of mass. Another drawback of the Smart Tab is the deteriorated aerodynamic performance of the profile. The center of pressure is not longer at 25% chord of the original profile body. For these reasons, only small Smart Tabs seem to be feasible.

The Active Trailing Edge seems to be more capable to achieve high authority. Higher deflections require larger and therefore heavier bending actuators. Due

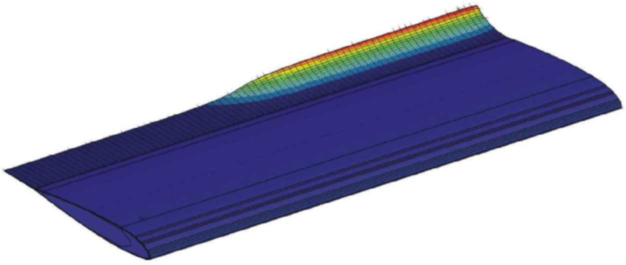


Fig. 3 : Continuous transition of passive to active trailing edge

to its smaller leverage to the blades neutral axis, less additional mass is needed to equilibrate the centre of masses of the ATE compared to the Smart Tab. Its stiffer design results in higher eigenfrequencies compared to the Smart Tab. A flexible filler material supports its airfoil shape.

Other advantages of the Active Trailing Edge are the smoothly deflected airfoil contour and the continuous transition between deflected and passive trailing edge in spanwise direction. This helps to reduce parasitic drag and discrete wake vortices of the deflected ATE compared to a servo flap. Figure 3 illustrates a deflected Active Trailing Edge and the continuous spanwise transition.

Furthermore, an Active Trailing Edge enables the design of an active blade tip. Since the ATE does not contain components close to the leading edge, it can be combined with varying blade chord and small airfoil thickness typical for a modern rotor blade tip.

3 INTERDISCIPLINARY OPTIMIZATION AND SIMULATION

The design of an adaptive helicopter rotor blade requires the close cooperation of different disciplines: Aerodynamics, structural dynamics, rotor dynamics, actuator technology, power electronics and control design are important issues.

For the Active Trailing Edge's bending actuator it is essential to consider both aerodynamic loads and structural deformation: On the one hand, the ATE should be as flexible as possible to achieve maximum trailing edge deflections and large aerodynamic effectiveness. On the other hand, the ATE must be stiff enough to carry the aerodynamic and blade dynamic loads.

An optimization study is done to determine the cross sectional geometry of the trimorph bender. The structural model is based on the Euler-Bernoulli beam theory. The aerodynamics are calculated using the classical thin airfoil theory with the Prandtl-Glauert compressibility correction. Each individual requires several fluid-structure iterations to obtain the coupled solution. The used evolutionary algorithm is described in [10].

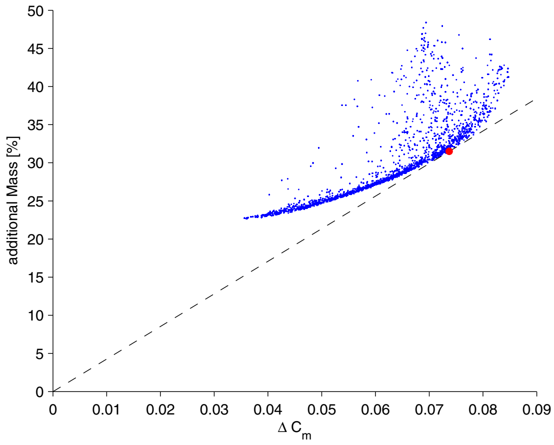


Fig. 4 : Pareto front of the optimization study

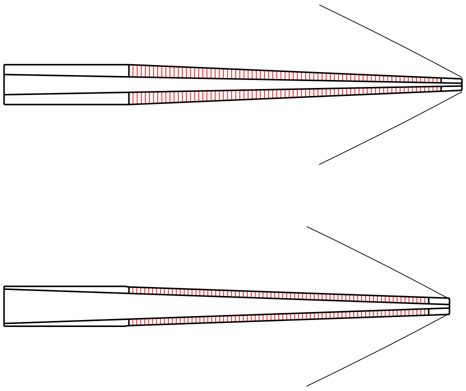


Fig. 5 : Optimized thickness distribution of active and core layers for different constraints

The degrees of freedom are the thickness distribution of piezo-ceramic and glass-fibre reinforced plastic core layers of the bender as well as its active chord length.

Target functions for the optimization are minimum additional mass and maximum aerodynamic effectiveness. Concerning the additional mass, not only the mass of the bending actuator but also the mass necessary to balance the centre of mass at 25% chord are taken into account. The aerodynamic effectiveness is calculated as difference of the aerodynamic moment coefficients of upwards and downwards deflection ΔC_m for an angle of attack of 0° and a Mach number of 0.6.

The constraints for the optimization are maximum allowable weight, piezo stress and geometry. The piezoceramic must not carry any tensile stress due to active deflection and aerodynamic forces or blade flapping accelerations. Since there is no reliable data about tensile strength and fatigue for the applied type of piezo-ceramics, this limit is fixed conservatively. To take the availability and manufacturing constraints of piezo actuators into account, the piezo thickness is either limited to a minimum of 0.3 mm or to be constant over the whole actuator length.

Figure 4 depicts a solution of the optimization study. Each point in the diagram represents a certain bender geometry. The Pareto front shows the points that achieve a certain ΔC_m with minimal possible weight. The optimum is chosen to be the minimal fraction of additional weight per ΔC_m. The tangent in the figure represents this minimum fraction. In Fig. 5, the optimal thickness distribution is shown for different constraints. The hatched areas represent the piezo layers. Other criteria for an optimal design are possible.

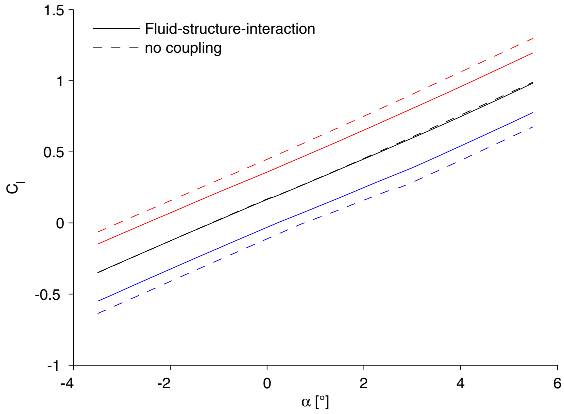
Figures 6(a)- 6(c) show the polars for the deflected Active Trailing Edge. The uncoupled and coupled solutions are presented for maximum upward and downward deflection, and neutral position. Aerodynamics are calculated using XFOIL. Compared to the uncoupled solution, the coupled solution gives a smaller effectiveness of the Active Trailing Edge due to the aerodynamic forces acting on the trailing edge in opposite direction to the active deflection. The aerodynamic loads show negligible influence for the Active Trailing Edge in neutral position. This is a desirable aeroelastically safe behaviour in the case of electrical failure. Figure 7 depicts the C_p distribution over the airfoil with deflected trailing edge.

A FEM study investigates the three-dimensional properties of the Active Trailing Edge. A rotor blade segment including the Active Trailing Edge is modelled in ANSYS.

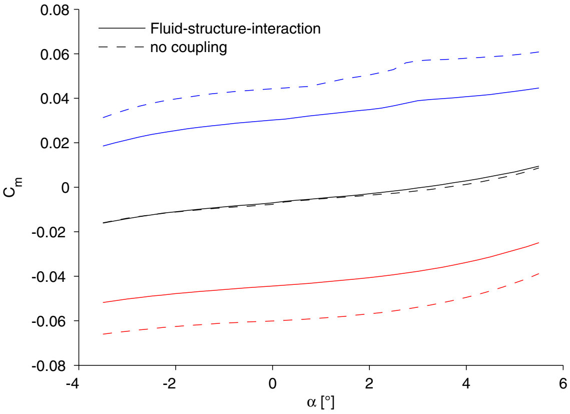
The deflection of the Active Trailing Edge due to the aerodynamic forces is calculated. These forces deflect the bender in opposite direction to its active deflection. Furthermore, the whole bender is rotated and displaced in its connection to the passive blade structure. Several layouts of this interface are regarded, see Fig. 8. It is found that the ATE requires a rigid connection to the passive rotor blade, similar to Fig. 8(c). Otherwise, a large part of its active deflection is lost due to deformation in a soft interface.

The occurring strains and stresses due to the limit loads of the reference rotor are determined. The relevant load cases are lead lag bending, flapping and torsional moments and centrifugal forces. The highest stresses in the trimorph bender occur due to lead lag bending. This load case induces high tensions and strains in the trailing edge of the passive blade structure particularly in spanwise direction. This strain is imposed on the trimorph bender if it is simply fixed to the passive structure. Various measures to reduce the tensile stress on the piezo-ceramic actuators are regarded.

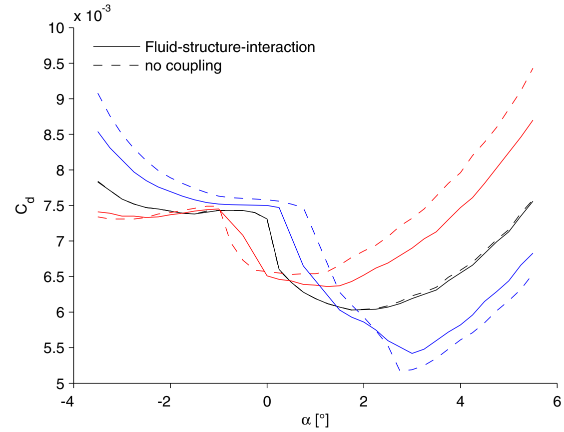
The desired material properties for the flexible filler are determined. The deformation of the Active Trailing Edge's profile due to the aerodynamic forces are calculated for varying Young's moduli of the flexible filler material. It is found that a Young's modulus



(a) $C_l(\alpha)$



(b) $C_m(\alpha)$



(c) $C_d(\alpha)$

Fig. 6 : Polars at $Ma = 0.6$ calculated with XFOIL

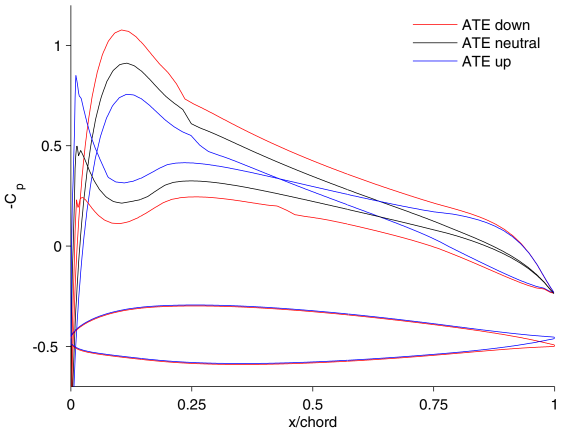
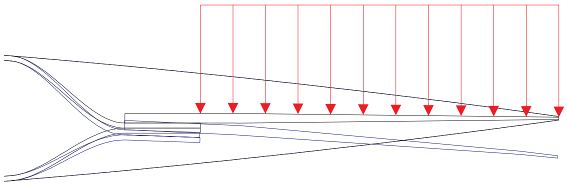
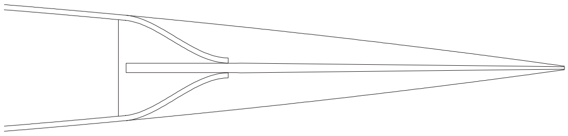


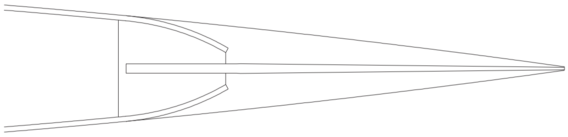
Fig. 7 : $C_p(x)$ for deflected airfoil at $\alpha = 0°$ and $Ma = 0.6$ calculated with XFOIL



(a) Layout 1



(b) Layout 2



(c) Layout 3

Fig. 8 : Connection of Active Trailing Edge and passive blade structure

smaller than 10 MPa is sufficient to sustain the rotor blade's profile.

For performance prediction, rotor dynamics simulations of an active rotor system equipped with the Active Trailing Edge are necessary. The choice of placement and dimensioning of the Active Trailing Edge depends on such simulations. Preliminary calculations predict adequate performance [11].

4 DESIGN AND MANUFACTURING OF AN ACTIVE TWIST DEMONSTRATOR

The ideal cross-sectional geometry for the Active Trailing Edge's bending actuator is determined from the optimization and some critical issues are identified by the FEM simulation. To realize a rotor blade equipped with the Active Trailing Edge, a more detailed design is necessary. A modular design allows to split the active rotor blade in separate parts: a modified passive rotor blade, the Active Trailing Edge and an interface between both.

The rotor blade design is modified in a way which allows to attach the Active Trailing Edge to it. The structural properties of the rotor blade such as stiffnesses and positions of the elastic axis, shear centre and centre of mass shall not be changed in the section of the Active Trailing Edge. The rotor blade houses the electric wires necessary to drive the ATE.

The Active Trailing Edge itself consists of the bending actuators and the flexible filler material. They are fixed in a host structure which enables mounting to the rotor blade and electrical contacting.

The connection between Active Trailing Edge and rotor blade should be stiff in the bending direction of the ATE in order to withstand the aerodynamic forces induced by the deflected trailing edge. At the same time, it should protect the ATE from large strains in spanwise direction and carry high centrifugal and flapping acceleration forces. This interface must also connect the Active Trailing Edge electrically.

The aim of this project is to design and build a full scale rotor blade segment equipped with an Active Trailing Edge. This segment shall be tested on a bending and torsion testing machine to proof operation of the ATE under static and dynamic blade loads. The design of the passive rotor blade is based on an existing rotor blade. The Active Trailing Edge will consist of several bender modules attached to the blade. Therefore, every bender module can be replaced separately. Each bender module will have its own power supply in order to be controlled individually. The flexible filler material is fixed to the trailing edge after the benders are mounted at the rotor blade.

The bender module's thickness distribution corresponds to the optimized data (Fig. 5). The core material is glass-fibre reinforced plastic. The passive material at the bender's root and tip is semi-finished GFRP material. The active material is piezo-ceramic. D_{33}-stack actuators are chosen due to their high active strain. Other actuators do not have sufficient active strain or do not offer the necessary thickness for the active plies of the trimorph bender, e.g. Active Fibre Composites (AFC) or Macro Fibre Composites (MFC) [12, 13].

Thin piezo-ceramic stack actuators are not available off-the-shelf in the geometry necessary for the Active Trailing Edge. Therefore the bender is assembled from smaller actuator tiles. Each of these tiles is electrically contacted. Figure 9 shows a bender module manufactured from 30 Noliac actuators. These low profile stack actuators are only 0.4 mm thick. The active deflection at an operating voltage of 180 V is ±2.75 mm. If a variable thickness of the piezo layers is desired, the bender needs to be further processed after

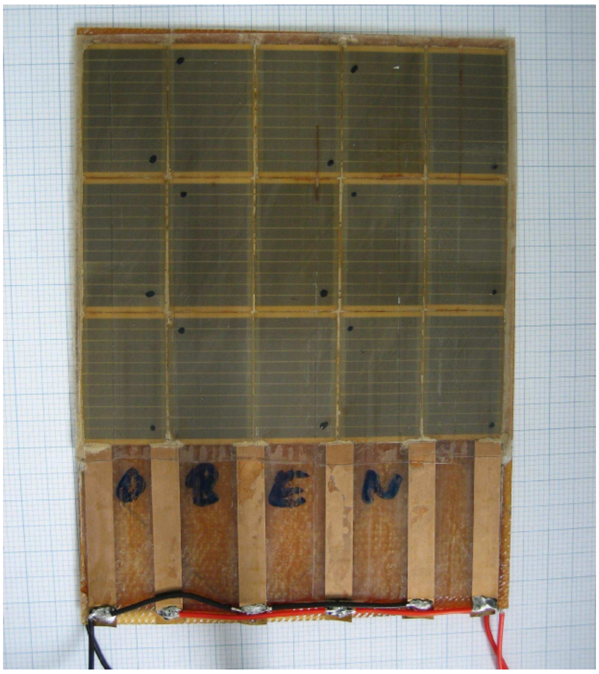


Fig. 9 : Active Trailing Edge bending actuator

curing. In the beginning, the bender module is manufactured from thicker piezo actuators. The benders surface is grinded on both sides to achieve the variable thickness. The direction of the electrodes is considered for the grinding process. The blank surfaces need to be coated before operation. Another critical issue for processing the bender are internal stresses which arise during curing.

A first functional specimen is build to demonstrate the working principle of the Active Trailing Edge, see Fig. 10. It features all basic components of the ATE concept. The trimorph bender is made up of 24 piezoceramic actuators and a glass-fibre reinforced plastic core. Piezo and core layer are of constant thickness. A robust electrical contacting of all actuators is necessary to avoid any electrical failure. There is a passive trailing edge tip of 15 mm length. The achieved active deflection is approximately ±2.5 mm at a operating voltage of 200 V. The temperature inside the Active Trailing Edge was measured on the surface of one of the piezo actuators. It did not exceed 65° C at frequencies up to 50 Hz at full operating voltage.

5 CONCLUSION

The Active Trailing Edge is a new actuation concept for active helicopter rotor blades. It consists basically of a trimorph bender integrated in the rotor blade's cross section without changing its aerodynamic shape in neutral position. Its working principle is the servo effect. Advantages are a smooth deformation of the trailing edge in chordwise and spanwise direction and a modular design.

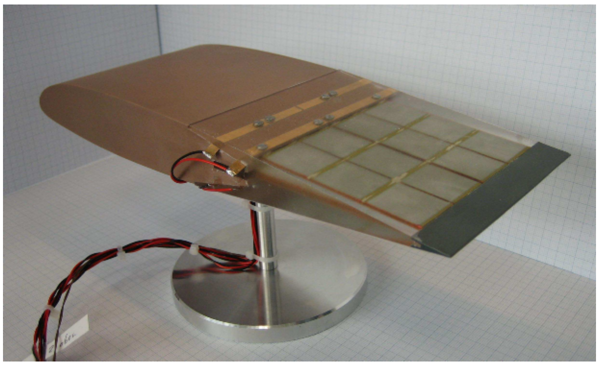


Fig. 10 : Functional demonstrator

The geometry of the active bender actuator of the Active Trailing Edge is optimized using an evolutionary algorithm. Finite element simulations helped to identify critical design issues. In addition, first benefit calculations predict adequate authority to reduce vibration and noise.

Bending actuator modules are developed to equip a rotor blade segment with an Active Trailing Edge for testing. First modules featuring low profile stack actuators have been build and tested successfully.

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