ACTUATOR DESIGN FOR THE ACTIVE TRAILING EDGE OF A HELICOPTER ROTOR BLADE

Christoph K. Maucher[1], Boris A. Grohmann[1], Peter Jänker[1], Andree Altmikus[2], Flemming Jensen[3], Horst Baier[4]

[1] EADS Innovation Works, Actuation and Smart Structures,
Willy-Messerschmitt Straße, 81663 München, Germany
E-mail: christoph.maucher@eads.net, Phone: +49 89 607 2 53 75

[2] Eurocopter Deutschland GmbH, Aerodynamics, OTEA/O,
Willy-Messerschmitt Straße, 81663 München, Germany

[3] Noliac A/S, Hejreskovvej 18, 3490 Kvistgaard, Denmark

[4] Institute of Lightweight Structures (LLB), TU München, 85747 Garching, Germany

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Abstract: Today, helicopters still suffer from their environmental impact regarding external noise, fuel consumption and emissions, their low passenger comfort regarding cabin noise and vibrations and their limited performance regarding flight envelope, speed and range. One of the main sources of noise and vibrations is the main rotor, especially in fast forward and descent flight. Therefore, technologies for advanced rotor control are investigated. Individual blade control (IBC) systems allow to reduce vibration, noise and shaft power consumption.
To control each rotor blade individually, on-blade actuation mechanisms based on active materials offer advantages in weight, power consumption and bandwidth compared to systems actuating the rotor blade root. The most advanced approaches so far are the direct twist concept and the trailing edge flap. The topic of this paper is a new concept for an IBC actuator, the Active Trailing Edge.
The Active Trailing Edge concept realizes 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, i.e. the change in aerodynamic pitching moment twists the rotor blade.

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 as well as active 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 around 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 these flight conditions. 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 smaller 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 be an additional source of 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, an advanced rotor control technology can reduce both noise and vibration by attacking at their source, the rotor aerodynamic loads.

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. In the 80s, HHC was demonstrated on several helicopters like OH-6A [4], S-76 [5] and SA 349 Gazelle [6] and wind tunnel tested [7]. 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 [8].

1.4 Actuation systems

The conventional swashplate is not applicable to control each blade individually. Therefore, appropriate actuation systems are necessary. The first helicopters equipped with an IBC system featured hydraulic systems actuating the blade root [9, 10]. Today, electro mechanical actuators are investigated [11]. On-blade actuation mechanisms based on active materials offer advantages in weight, power consumption and bandwidth [12]. The most advanced approaches so far are active twist control and trailing edge servo flaps. Table 1 shows some examples of Active Rotor Blade Projects realized in the recent decade.

	Active Twist	*Trailing Edge Flap*	*further concepts*
Model Scale	DLR/ONERA: 1:2.5 scale rotor blade [13] Boeing/MIT: 1/6th scaled CH-47 Rotor and AMR Rotor [14] NASA/Army/MIT: Active Twist Rotor ATR [12] U.S. Army Vehicle Technology Directorate: Advanced Active Twist Rotor AATR [15]	ONERA/DLR/Eurocopter: DTP RPA (Développement Technique Probatoire Rotor à Pale Active) or ABC (Active Blade Concept) [16] Boeing/MIT: 1/6th scaled CH-47 Rotor [17] McDonnell Douglas: Active Flap Model Rotor [18] JAXA, Mitsubishi Heavy Industries: Model rotor [19] University of Maryland, Alfred Gessow Rotorcraft Center: Mach-scaled rotor with trailing edge flaps [20]	Auburn University: Solid State Adaptive Rotor [21]
Full Scale	Boeing: Active Low Vibration Rotor CH-47 [22]	Boeing: SMART Active Control Flap [23] Eurocopter/EADS IW: ADASYS [24] Diversified Technologies: Heliflap [25] JAXA: Full Scale On-board Active Flap System [26] Kawasaki Heavy Industries: Full Scale Rotor System including active flap system and HHC actuators [27]	Diversified Technologies: LEEMA (Leading Edge Electro Magnetic Airfoil) [28] PenState University: Gurney Flap [29] DLR/EADS IW: Leading Edge Flap [30] Boeing: SMART Trim Tab [23] Alfred Gessow Rotorcraft Center: SMA actuated trimtab [31] Eurocopter/EADS IW: Active Trailing Edge

Table 1. Some examples of Active Rotor Blade Projects in the recent years

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 fibers in the rotor blade's skin. The active fibers are arranged in a way which induces 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 [15]. A segment of an active twist blade in full-scale is presented in [22]. 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 [24, 32]. 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.

Figure 1: BK117 equipped with servo flaps

1.5 Requirements for an active rotorblade

The design for an adaptive rotor blade must fulfill the requirements for a standard passive rotor blade. The actuation must be integrated into the aerodynamic shape. The additional weight should be as small as possible. It is important to keep the center of gravity at the 25% chord line. Changes in weight distribution and stiffness influence the dynamic properties of the rotor. The resonance frequencies must be well tuned. An adaptive rotor should match flap and bending stiffness of a passive design. The torsional stiffness could be reduced to 50%-70% compared to a passive blade.
Loads acting on a rotor blade are high centrifugal forces and flapping accelerations, lead-lag bending, flapping and torsions. The actuation mechanism of an active blade must either be protected against or withstand these forces and the large strains of the blade structure.
The manufacturing process of the adaptive rotor blade should be compatible with the baseline manufacturing approach. A certain modularity of the active devices seems to be desirable in order to facilitate maintenance and repair of an active rotor.

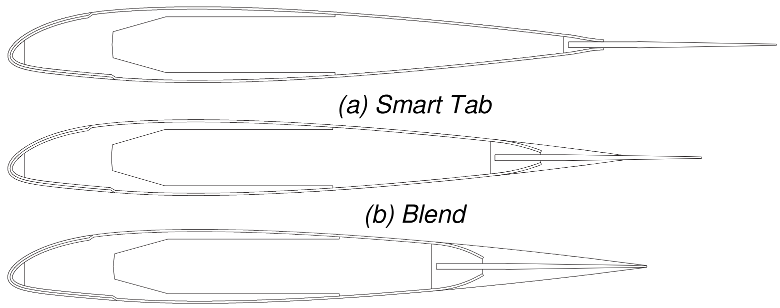
2 ACTIVE TRAILING EDGE CONCEPT

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.
The Active Trailing Edge concept realizes a morphing cross section for a helicopter rotorblade. 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-fiber 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 center 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.



(a) Smart Tab

(b) Blend

(c) Active Trailing Edge

Figure 2: Smart tab versus Active Trailing Edge

The Active Trailing Edge seems to be more capable to achieve high authority. Higher deflections require larger and therefore heavier bending actuators. Due to its smaller leverage to the blades neutral axis, less additional mass is needed to equilibrate the center of masses of the ATE compared to the Smart Tab. Its stiffer design results in higher resonance frequencies 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.

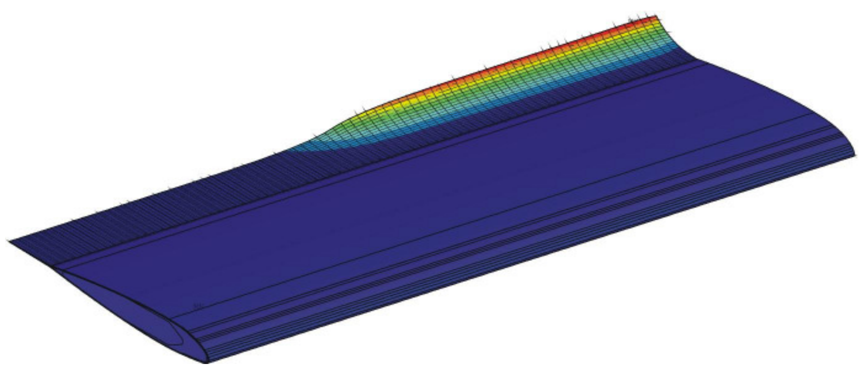


Figure 3: Continuous transition of passive to active trailing edge

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. The used evolutionary algorithm is described in [33].
The degrees of freedom are the thickness distribution of piezo-ceramic and glass-fiber 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 center 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 piezo-ceramic 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 0.3mm or to be constant over the whole actuator length. Constraints corresponding to other actuator technologies result in different optimum designs.

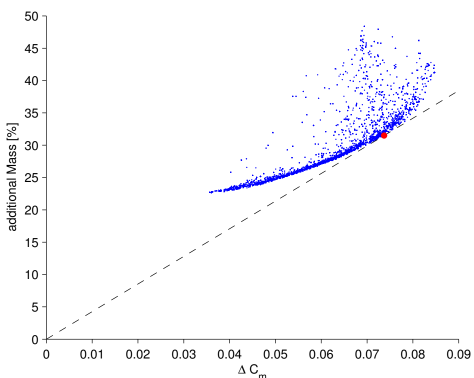


Figure 4: Pareto front of the optimization study

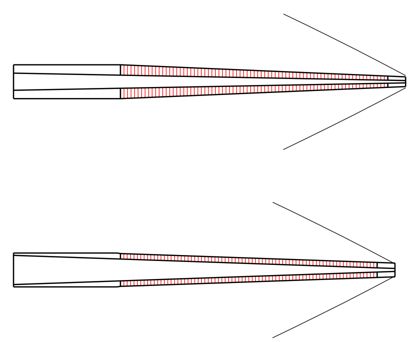
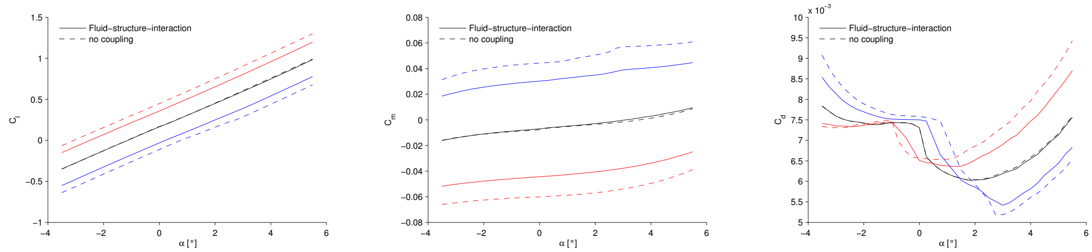


Figure 5: Optimized thickness distribution of active and core layers for different constraints

Figure 4 depicts a solution of the optimization study. Each point in the diagram represents a certain bender geometry. Several fluid-structure iterations are necessary to obtain its coupled solution. 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 the 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 behavior in the case of electrical failure. Figure 7 depicts the C p distribution on the airfoil with deflected trailing edge.



(a) $C_l(\alpha)$ (b) $C_m(\alpha)$ (c) $C_d(\alpha)$

Figure 6: Polars at Ma = 0.6 calculated with XFOIL

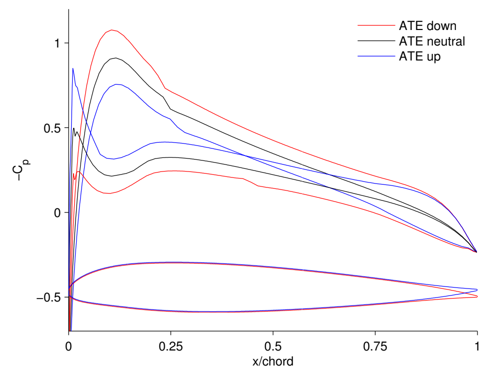
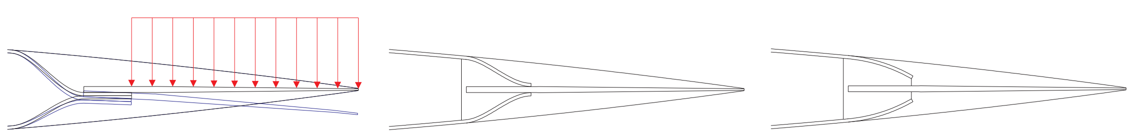


Figure 7: $C_p(x)$ for deflected airfoil at $\alpha = 0°$ and Ma = 0.6 calculated with XFOIL

A FEM studies investigate the three-dimensional properties of the Active Trailing Edge. A detailed bending actuator module and a rotor blade segment including the Active Trailing Edge are modeled 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 generic 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.



(a) Layout 1 (b) Layout 2 (c) Layout 3

Figure 8: Connection of Active Trailing Edge and passive blade structure

To validate laboratory tests, the detailed model of the bending module is adapted to the tested hardware. Deflection and strains occurring due to active bending and external forces are calculated, see Fig. 11.
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 piezoceramic 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 smaller than 10MPa 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 [34].

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 center and center 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.

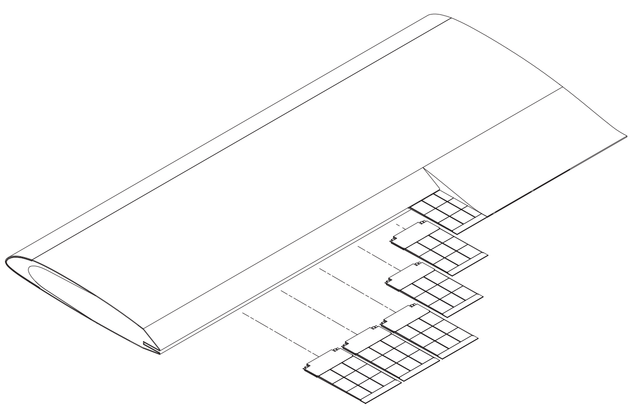


Figure 9: Integration of actuator modules into rotor blade segment

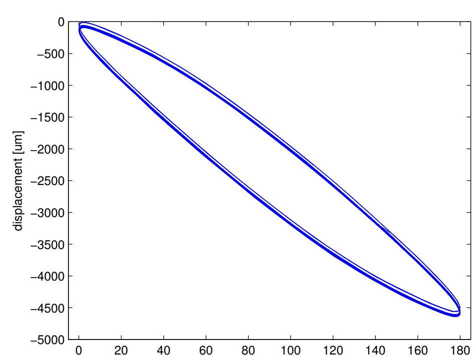


Figure 10: active deflection of a ATE bender module at full operating voltage

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 structure is based on an existing rotor blade. Design and manufacturing is done at

Eurocopter. 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, see Fig. 9.
The bender module's thickness distribution corresponds to the optimized data (Fig. 5). The core material and the passive material at the bender's root and tip is glass-fiber reinforced plastic. The active material is piezo-ceramic. D33-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 Fiber Composites (AFC) or Macro Fiber Composites (MFC) [35, 36].
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. These low profile stack actuators are only 0.4mm thick. Since ceramics are a brittle material, such a thin actuator is very sensitive to micro-damages leading to a piezo failure in operation. In order to assure the quality of the bender, each of the tiles is tested before assembling the bending modules. A number of $1 \cdot 10^7$ cycles is regarded as sufficient since no failure occurred during longer tests.
The bending actuator is manufactured in a vacuum prepreg process. Each of the 24 actuator tiles is electrically contacted during this process.
Several benders have been manufactured and tested. The active deflection at an operating voltage of 180V is ±2.2mm, see Fig. 10. Due to a smaller active strain of the LPS actuators, the deflection is smaller than predicted in the optimization study. If the calculation is adjusted to the measured active strain, they fit the deflection of the module.

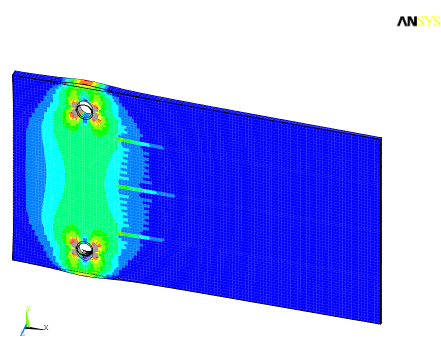


Figure 11: ANSYS model of the bending actuator: Elastic strain due to tensile force in spanwise direction.

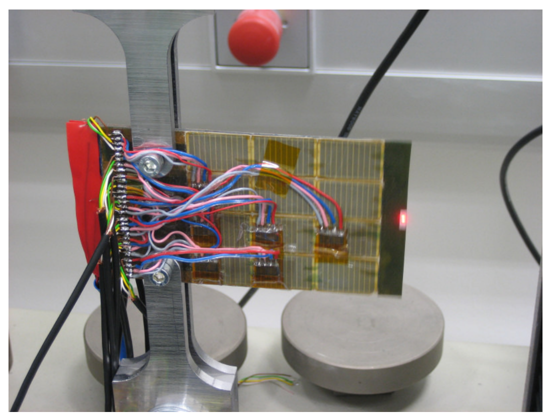


Figure 12: Active Trailing Edge bending actuator in tensile test

Endurance tests proved the modules ability to run for over $1 \cdot 10^8$ cycles without failure at full operating voltage. A bender equipped with strain gauges proved the ability to operate under tensile forces, see Fig. 12. The acquired data fits the prediction of FEM analysis (Fig.11).
If a variable thickness of the piezo layers is desired, the bender module needs to be further processed after curing. 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. To proof this concept, a bender with a variable thickness corresponding to the optimized geometry was manufactured and tested successfully 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.

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.

Acknowledgement

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