ACTUATION CONCEPTS FOR MORPHING HELICOPTER ROTOR BLADES

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Abstract

Actuation concepts for deforming helicopter rotor blades with the aim to control rotor aerodynamics are presented. Focus is on blade twist and airfoil camber variation and the two relevant aerodynamic working principles, i.e. direct lift and servo effect are discussed. The proposed actuation concepts are based on piezoceramtic actuation with focus on d33-mode. These actuation concepts are analysed in detail. Comparison of different configurations is accomplished. For the Active Trailing Edge concept, results of aero-servo-elastic optimization studies and the corresponding actuator performance in terms of aerodynamic effectiveness as well as actuator mass are presented. Furthermore, integration issues, relevant requirements and restrictions are discussed. Finally, piezoceramic actuator arrays developed for the Active Trailing Edge concept are presented.

1 Introduction

Today's helicopters need to be further improved with respect to environmental and public acceptance, especially external and cabin noise, vibration for passenger comfort, fuel consumption, performance, component life, etc. There is significant potential for improvement especially in forward flight which creates very different aerodynamic conditions on the rotor blades during each revolution.

For this purpose, a lot of research has been done during the last decades and several adaptive helicopter rotor blade concepts have been developed. The most popular concepts so far include the direct twist concept and trailing edge flaps [6].

To realize these concepts appropriate actuation systems are necessary. For adaptive helicopter rotor blades, piezoceramic actuators have been widely employed and significant progress in actuation technology is expected in the near future.

This paper aims on technology investigated at EADS Corporate Research Center with a focus on the "smart aerostructures" paradigm, i.e. structurally integrated smart material actuation. Results presented are based on a generic Bo105 reference rotor with NACA23012 airfoil.

2 Blade Twist

Blade twist aims at the spanwise variation of lift distribution without affecting aerodynamic pitching moment. Blade twist is achieved by immediate, structure-borne twist actuation.

A vast amount of literature [6] report the development of active twist rotor blades. Recent developments include model scale [7] and full scale [9].

The purpose of the current investigation is a simple parametric design study exploring the potentials with respect to achievable blade twist and additional actuator mass. Results are presented for a Bo105 full scale blade with 270mm chord.

The baseline Bo105 blade features a C-spar made of GFRP, a GFRP torsion skin and erosion protection in the leading edge area. Based on this configuration, piezoceramic layers are added to the blade skin. The piezoceramic layers are working in d33-mode. The orientation of the piezoelectric d33-direction is 45^o with respect to spanwise direction, see Fig. 1

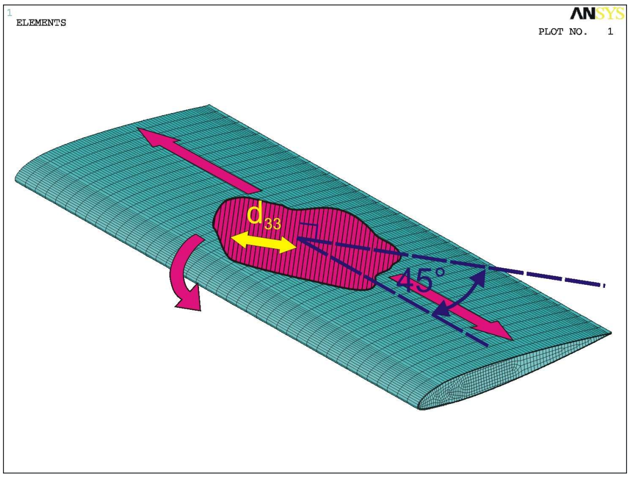
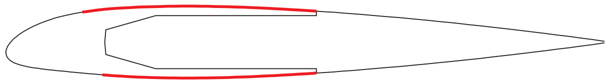
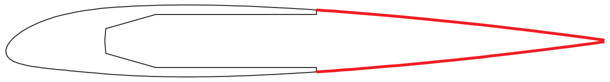


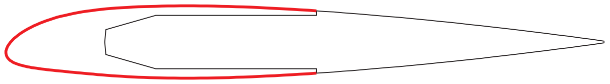
Fig. 1 Orientation of piezoelectric effect for blade twist actuation



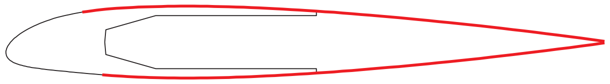
(a) blade twist concept #1



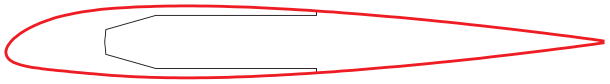
(b) blade twist concept #2



(c) blade twist concept #3



(d) blade twist concept #4



(e) blade twist concept #5

Fig. 2 Location of piezoelectric actuator layers of different blade twist concepts

Different placement of piezoceramic layers is investigated according to Fig. 2. Furthermore, the option of a D-spar is investigated by adding a bar at the rear end of the original C-spar.

The piezoceramic layers of concept #1 reach from the erosion protection to the rear end of the C-spar, see Fig. 2(a). In concept #2 the piezoceramic layers reach from the C-spar downstream to the trailing edge, see Fig. 2(b). Concept #3 is similar to concept #1 but the leading edge area is also covered by piezoceramics with potential issues concerning curvature of the piezoceramic actuators and integration with the erosion protection, see Fig. 2(c). In concept #4 the piezoceramics reach from the erosion protection downstream to the trailing edge, see Fig. 2(d). In concept #5 the whole blade is covered by piezoceramics, see Fig. 2(e).

All concepts comprise constant thickness of the piezoceramic layers of 0.5 mm. Note that piezoceramic surfaces are curved according to the original NACA23012 airfoil shape.

Assuming constant blade setup in spanwise direction, Fig. 3 depicts a comparison of concept performance in terms of achievable twist angle per span, additional actuator mass per span and the position of center of gravity (c.g.).

Please note that for this preliminary concept performance evaluation, the finite element model has been simplified concerning integration of active material layers: piezoceramic layers are simply added on top of the blade skin of the baseline configuration. The resulting rotor blade is not modified in order to keep cross sectional properties constant.

It is seen that concept #1 including D-spar (="1D") is most efficient in terms of additional mass to twist angle ratio. However, concept #1 has the lowest absolute performance in terms of active twist. Concepts #1 and #3 feature the most advantageous position of center of gravity in the vicinity of 25% chord while the other concepts' position of center of gravity is behind 30% chord.

It is seen that the influence of the optional D-

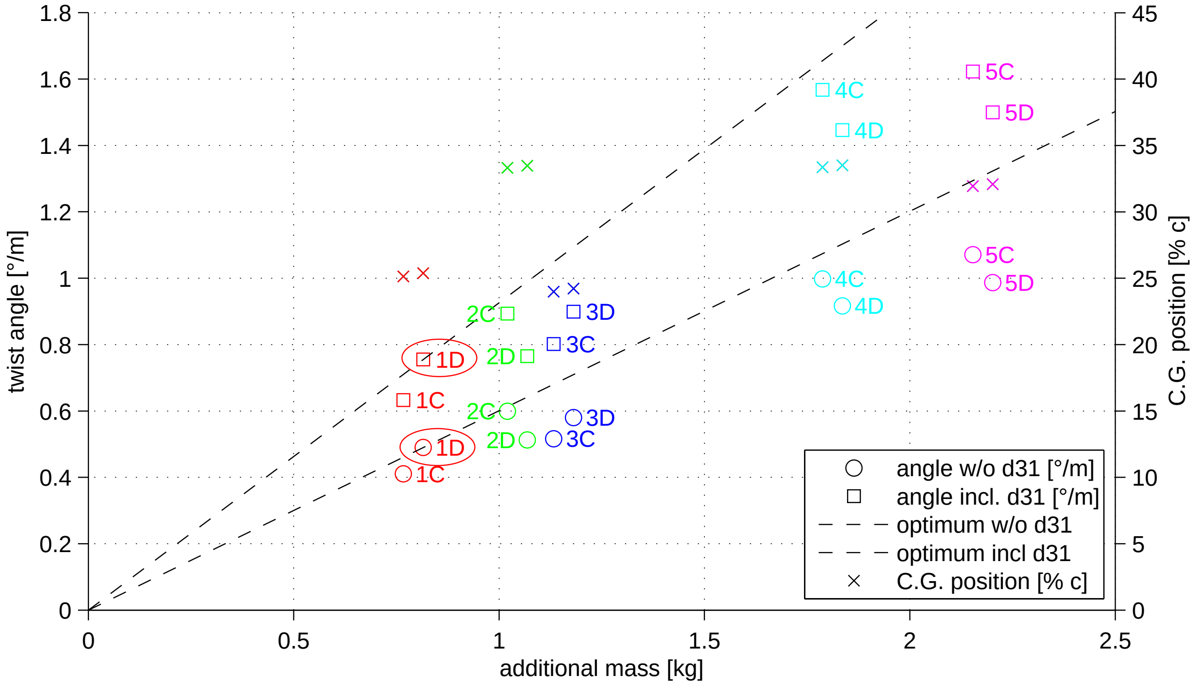


Fig. 3 Comparison of twist performance, additional mass and center of gravity for different actuator layouts

spar varies between concepts: for concepts #1 and #3 the D-spar increases twist angle performance while it has adverse effect on concepts #2, #4 and #5.

Fig. 3 includes an finite element study of the influence of d31-effect on the total twist performance. It is clearly seen that the absence of d31-actuation decreases total performance.

Furthermore, the effect of varying piezo thickness was studied for concept 1D. In Fig. 4 it is seen that efficiency in terms of twist angle per applied piezo mass decreases for increasing active material layer thickness.

According to this quasi-steady analysis assuming a free active piezoelectric strain of 0.16%, it is seen that an active twist in the order of 1^o/m may be achieved. Further studies are necessary to deal with issues like integration of erosion protection, conformability of piezoceramic actuators for curved airfoil surfaces, maximum allowable aft position of center of gravity and optimization of blade layout, especially actuator thickness distribution.

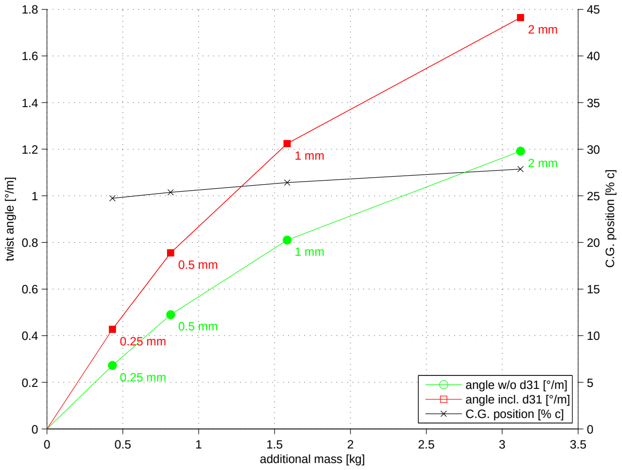


Fig. 4 Comparison of twist performance, additional mass and center of gravity for varying piezo thickness of concept 1D

3 Airfoil Camber

While active twist concepts aim at the variation of lift without affecting pitching moment, airfoil camber may be generally employed for both the control of lift and pitching moment in combination. Furthermore, the location of camber variation at the leading or trailing edge and the type of camber variation, e.g. reflexed shape, have significant effect on airfoil aerodynamics.

3.1 Discrete Flaps

Discrete flaps are the simplest means to realize camber variation and are widely used in all types of aircraft. Different design options exist to implement the necessary hinge as key element, e.g. different types of industry standard bearings.

3.1.1 Leading-Edge Flap

Leading-edge flaps are employed for dynamic stall alleviation, i.e. in order to increase maximum airfoil lift without separation and undesirable side-effects on pitching moment. Their aerodynamic effectiveness has been demonstrated experimentally [2, 5].

3.1.2 Servo Flap

Blade twist may be achieved via the so-called servoeffect of a trailing edge flap, i.e. aerodynamic pitching moments generated by flap deflection. Developments include model scale [8] and full scale. The system depicted in Fig. 5 has been successfully flown in 2005 on a BK117 helicopter [1]. The corresponding actuation system based on piezoceramic stack actuators is described in [4].

3.2 Active Trailing Edge

Similar to the trailing edge servo flap with discrete hinge, continuous blade trailing edge defornation may be realized. For this purpose, an Active Tab may be attached to the trailing edge of the baseline helicopter rotor airfoil or the Active Trailing Edge actuator may be integrated into the airfoil [3]. The Active Trailing Edge actuator is realized by a multi-morph bender including piezoelectric ceramics, glass fibre reinforced plastics and further components.

Advantages of the Active Trailing Edge concept are a smoothly deflected airfoil contour in chordwise direction and no gaps at the ends of the arodynamically active surfaces in spanwise direction. This leads to the avoidance of parasitic drag and discrete wake vortices when the ATE is deflected. Figure 6 depicts the deformed Active Tab geometry with a maximum active deflection at the trailing edge of $\hat{w}_{te} \approx 3.7mm$ without aerodynamic loads.

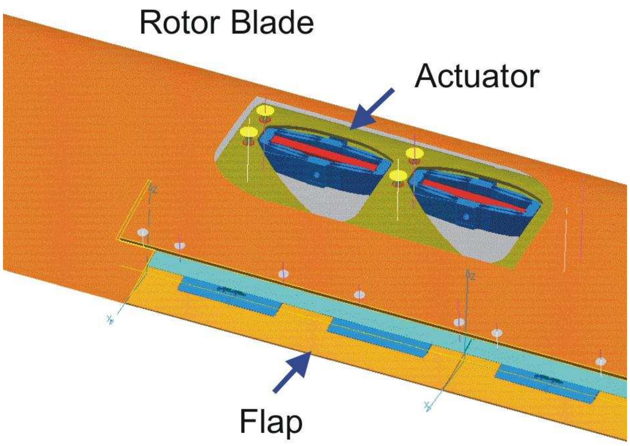


Fig. 5 Trailing Edge Servo Flap piezoelectric actuation module

The Active Trailing Edge is placed in the outer region of the rotor blade. For this reason, the actuator is only subjected to reduced structural loads in comparison to the blade root, especially centrifugal loads. Due to the modular design of the Active Trailing Edge actuator, maintenance is simplified and the actuator may be easily detached from the host blade structure for replacement.

Design and optimization of adaptive helicopter rotor blades require an interdisciplinary effort including structural mechanics, aerodynamics, rotor-dynamics, actuator technology, power-electronics and control.

Even concerning the optimization of the Active Trailing Edge actuator itself, it is essential to apply a multidisciplinary approach considering aerodynamic loads and active shape deformation: on the one hand, the aero-servo-elastic optimization requires the smart aerostructure to be as flexible as possible for large active deflections leading to large aerodynamic effectiveness. On the

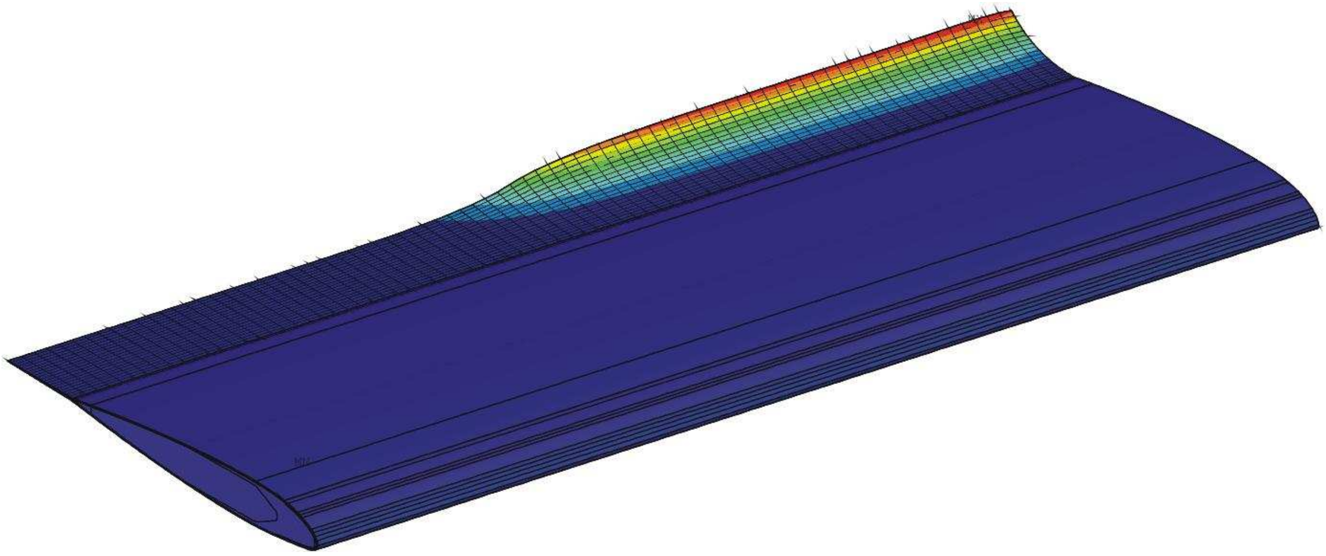


Fig. 6 Active Trailing Edge smooth blade shape deformation

other hand, the structure has to be stiff enough to carry aerodynamic loads.

Target functions for optimization may be minimum mass, minimum electric power consumption, maximum aerodynamic effectiveness. Concerning mass, not only the mass of the piezoelectric actuator itself, but also for potential balancing weight in order to keep the centre of mass at 25% chord and the weight of necessary structural interfaces should be considered. Even the mass of necessary system components like power amplifiers (depending on power consumption) may be relevant from an actuation system point of view. Concerning aerodynamic effectiveness, pitching moment (design for servo effect) or lift (design for direct lift effect), additional drag (airfoil drag, induced drag, stall or transonic effects) may be considered. However, simple geometric properties like trailing edge deflection may be misleading concerning aerodynamic effectiveness for the current type of integrated aero-servo-elastic actuation system.

3.2.1 Servo Effect

Similar to the previously developed trailing edge flaps depicted in Fig. 5, the rotor blade dynamics may be primarily controlled via the servo effect, i.e. generation of aerodynamic pitching moments twisting the blade. In this case, target functions for actuator optimization are maximum pitching moment and minimum additional mass.

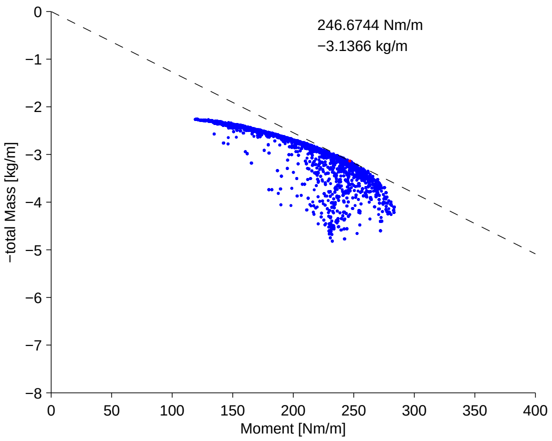
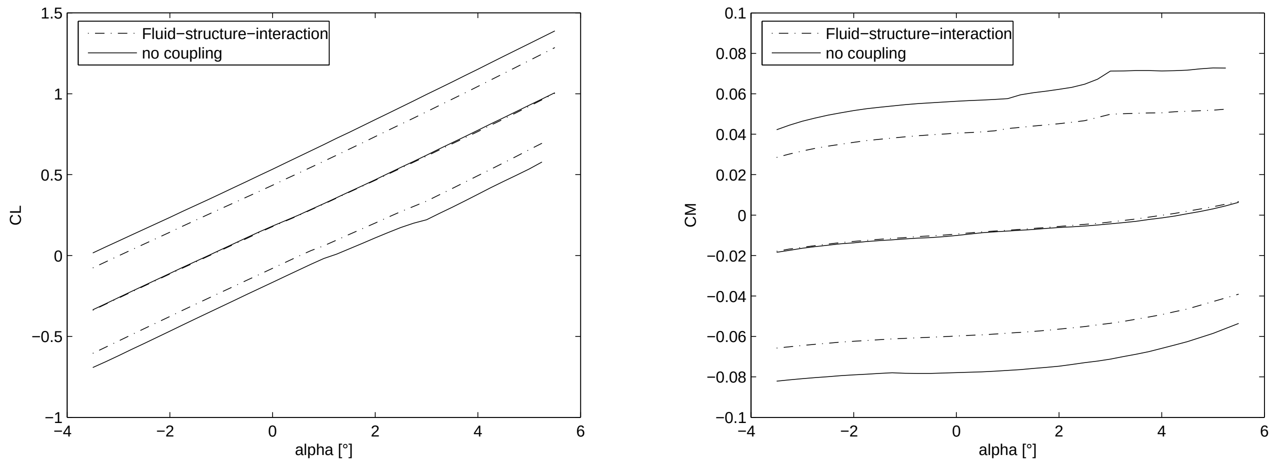


Fig. 7 Optimization of Active Trailing Edge actuator concerning additional mass versus aerodynamic effectiveness in terms of pitching moment: example Pareto front and tangent representing best performance ratio

Figure 7 depicts a comparison of different Active Trailing Edge designs for a total chord of 362mm. The mass per unit span comprises the mass of the piezoelectric actuator itself and also the balancing lead weight in the blade lead-



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

Fig. 8 Aero-servo-elastic polars of Active Trailing Edge at $Ma = 0.6$

ing edge in order to keep the centre of mass at 25% chord. During optimization, aerodynamics are computed employing compressible potential theory at Ma=0.6.

Optimization parameters include geometric properties of the actuator like piezozeramic chord length and thickness distribution of piezoceramic and GFRP layers. Constraints include maximum allowable stresses for piezo and GFRP, especially tensile stresses in piezoceramics based on classical laminated plate theory.

The tangent to the Pareto front, i.e. the boundary of best possible designs, yields the best possible performance ratio of pitching moment to additional mass.

Applying Fig. 7 for Active Trailing Edge actuator optimization, it must be considered that the final trade-off between pitching moment and additional mass must take into account overal blade design and rotordynamic effectiveness.

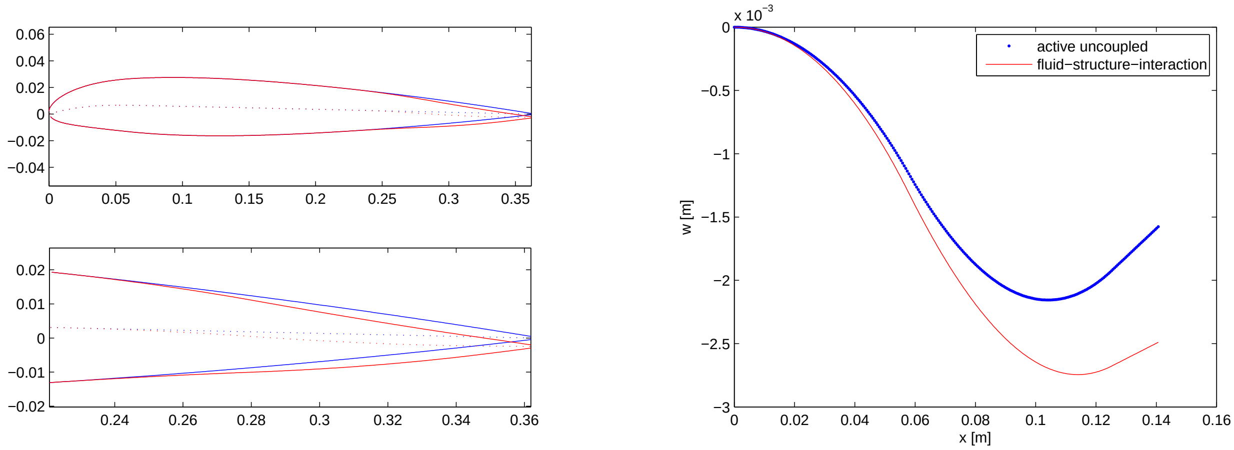
Figure 8 depicts example aero-servo-elastic polars for a blade section with NACA23012 airfoil, total chord $c = 350mm$ and an Active Trailing Edge piezoelectric actuator. It is seen, that aerodynamic loads, i.e. aero-servo-elastic coupling has significant influence on aeodynamic effectiveness. From Fig.8(b) it is seen that a servo effect $\Delta C_m = \pm 0.05$ may be achieved corresponding to a trailing edge servo flap with deflection $\Delta\beta \approx \pm 5^o$ and chord $c_{flap}/c \approx 1/5$ according to inviscid potential aerodynamics. Furthermore, the aerodynamic loads show negligible influence in both Fig. 8(a) and Fig. 8(b) for the actuator neutral, i.e. inactive position. This represents the desirable aero-elastically safe behaviour in the case of electrical (actuator) failure.

3.2.2 Active Reflexed Skeleton Line

Direct lift effect without influence on pitching moment may be obtained by an active reflexed skeleton line. This may also be realized by the Active Trailing Edge concept with appropriate actuator control, i.e. deflection like an "S" shape, see Fig. 9.

In this case, the target functions for actuator optimization are to maximize influence on lift coefficient, minimize influence on pitching moment and minimize additional mass while maintaining center of gravity at 25% chord.

An example layout is depicted in Fig. 9(a). The total chord of the Active Trailing Edge is $141mm \approx 39\%$ chord whith $125mm \approx 34\%$ chord piezo. The active reflexed skeleton line is achieved by deflecting the Active Trailing Edge in one direction at its upstream root while the downstream $67mm \approx 18\%$ chord portion is deflected inversely. The aerodynamic performance of this example layout according to thin airfoil



(a) Active Trailing Edge shape: original NACA23012 shape (blue) and active deflection including fluid-structure interaction (red)

(b) Comparison of deformation of Active Trailing Edge skeleton line with (red solid) and without (blue dotted) fluid-structure interaction

Fig. 9 Active Trailing Edge with reflexed skeleton line

theory with Prandtl-Glauert compressibility correction is $\Delta C_l \approx 0.138$ equivalent to a change of angle of attack of a flat plate of $\Delta\alpha \approx 1.25^o$. The corresponding change of pitching moment may be considered negligible $\Delta C_m \approx 0$.

In Fig. 9(b) the skeleton line is depicted in detail. In this particular case, the aero-servo-elastic coupling leads to an effect similar to FLETTNER's servo-rudder.

Design studies show that effectiveness concerning lift coefficient may be doubled in comparison to the example actuator design presented above, e.g. $\Delta C_l \approx 0.28$ corresponding to a change of angle of attack of a flat plate $\Delta\alpha > 2.5^o$ if moderate influence on pitching moment coefficient is accepted $\Delta C_m \approx 0.045$ which is approximately half the value of the Active Trailing Edge optimized for maximum servo effect.

The trade-off between influence on lift coefficient and influence on pitching moment also leads to different actuator masses.

It should be emphasized that it is generally possible to design and setup an Active Trailing Edge actuator in a way to enable multi-functional use as both servo and direct lift device.

3.2.3 Active Blade Tip

An active blade tip enables the control of tip vortices (blade-vortex interaction, BVI) and transonic effects (high-speed impulsive noise, HSI). In contrary to the trailing edge servo flap, the Active Trailing Edge actuator may be quite easily integrated into an advanced blade tip. Since the Active Trailing Edge does not contain components close to the leading edge, it can be combined with varying blade chord and small airfoil thickness typical for a parabolic blade tip, see Fig. 10.

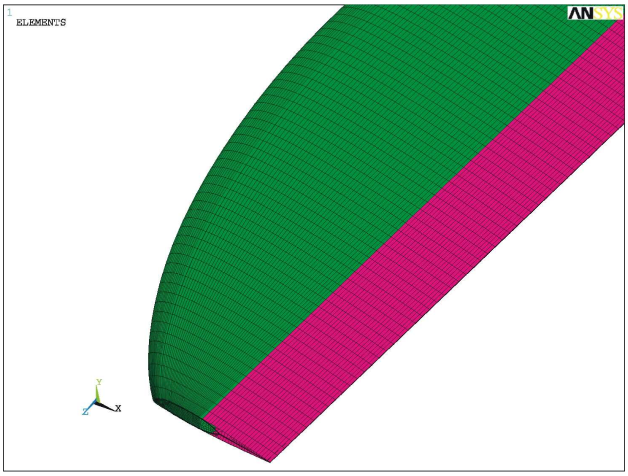


Fig. 10 Active Trailing Edge integrated into blade tip

3.2.4 Piezoelectric Actuator Technology

Current adaptive helicopter rotor concepts like active blade twist are based on large assemblies of piezoelectric actuators integrated in composite structures, e.g. glass fibre reinforced plastics (GFRP). For simplifying the manufacturing process, different packaging technologies of piezoelectric actuators have been developed [10], e.g. macro fibre composite (MFC) actuators.

Figure 11 depicts a 5x3x2 array manufactured from 15x24x0.4mm^3 NOLIAC piezoceramic stack actuators developed for the Active Trailing Edge. Active deflection at full operating voltage $U_{pp} = 180V$ is $\pm 2.75mm$.

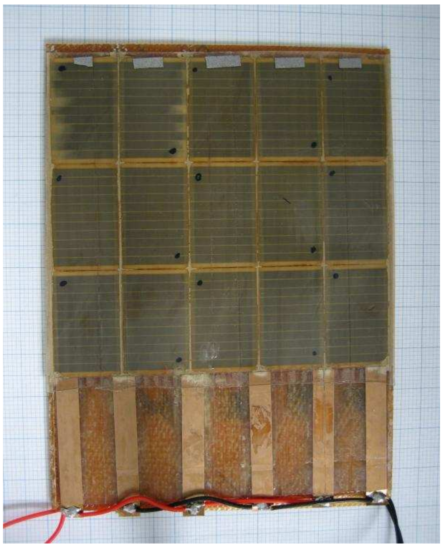


Fig. 11 Array of piezoceramic stacks for multimorph bending actuator

Fig. 12 depicts an Active Trailing Edge actuator demonstrator featuring 75mm piezo chord and 270mm total chord. Due to manufacturing restrictions concerning thickness of piezoceramic actuators, active deflection at the trailing edge is limited to approximately $\pm 2.5mm$ at full operating voltage $U_{pp} = 200V$. For demonstration purposes, the piezoceramic Active Trailing Edge actuator is covered with transparent silicone.

4 Conclusions

Several actuation concepts for deforming helicopter blades have been presented with focus on active twist and camber variation.

In the case of blade twist, placement of active material layers has significant effect on achievable twist preformance, additional mass and blade cross-section properties like location of center of gravity. Further detailed full-scale studies are necessary to optimize the blade layout and actuator integration.

In the case of airfoil camber variation, the Active Trailing Edge concept has been proposed based on the successfully flight-tested trailing edge servo flap. Aero-servo-elastic optimization studies have been executed to analyze the trade-off between aerodynamic effectiveness in terms of direct lift or servo effect and additional mass while maintaining the center of gravity at 25% chord.

Advantages of the Active Trailing Edge concept are a smoothly deflected airfoil contour in chordwise direction and no gaps at the ends of the arodynamically active surfaces in spanwise direction. Due to the modular design of the Active Trailing Edge actuator, maintenance is simplified and the actuator may be easily detached from the host blade structure for replacement.

Piezoceramics have been proven to be suitable actuation technology for morphing helicopter rotor blades. Main advantages are electrical power supply, robustness concerning hostile environmental conditions, especially vibration, and high bandwith. Focus on recent developments has been on d33-mode actuation where significant improvement has been achieved.

Worldwide, several adaptive helicopter rotor concepts have been proven from a scientific or technological point of view. However, the proof of their commercial benefit for the helicopter market including cost, reliability and maintenance issues is still pending. For this reason, future development efforts will increasingly focus on reliability (e.g. redundancy), integration as well as manufacturing issues and cost.

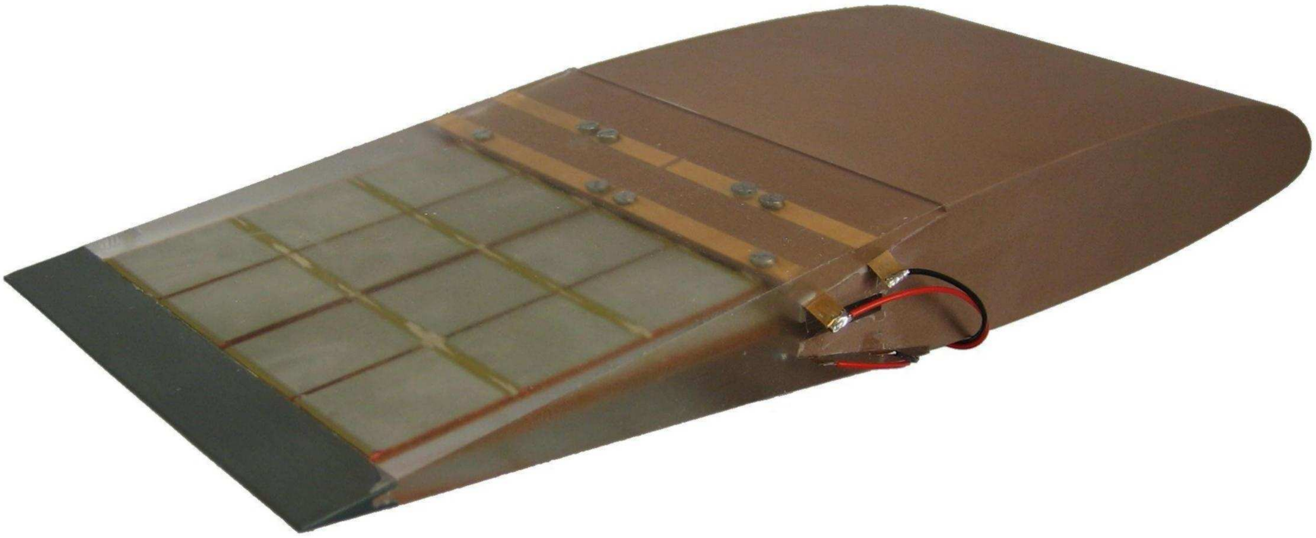


Fig. 12 Active Trailing Edge actuator demonstrator

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