PIEZOCERAMIC ACTUATORS FOR MORPHING HELICOPTER ROTOR

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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 corresponding aerodynamic working principles, i.e. direct lift and servo effect are discussed.

The proposed actuation concepts are based on piezoceramic 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 are presented. Evolutionary algorithms are employed for aero-servo-elastic optimization and target functions for optimization are minimum mass and maximum aerodynamic effectiveness. 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 [1] and trailing edge flaps [2].

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 Innovation Works 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 [2] report the development of active twist rotor blades. Recent developments include model scale [3] and full scale [4].

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

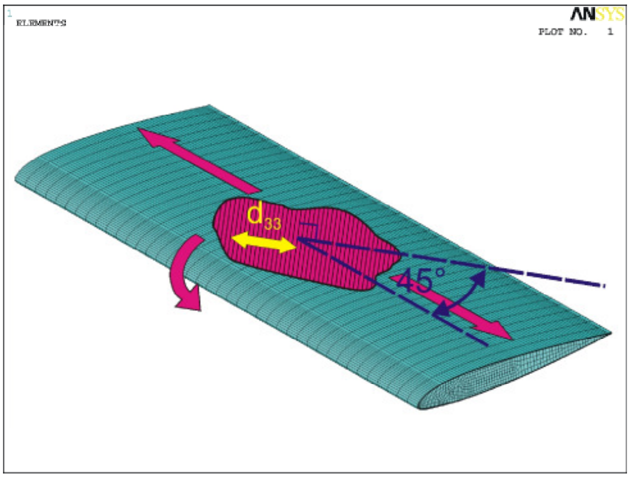
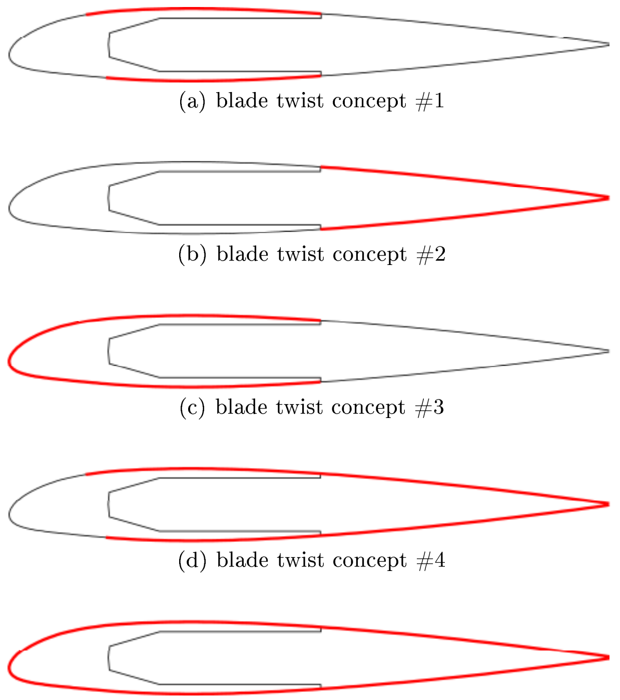


Fig. 1 : Orientation of piezoelectric effect for blade twist actuation

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).



(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

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-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 a 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.

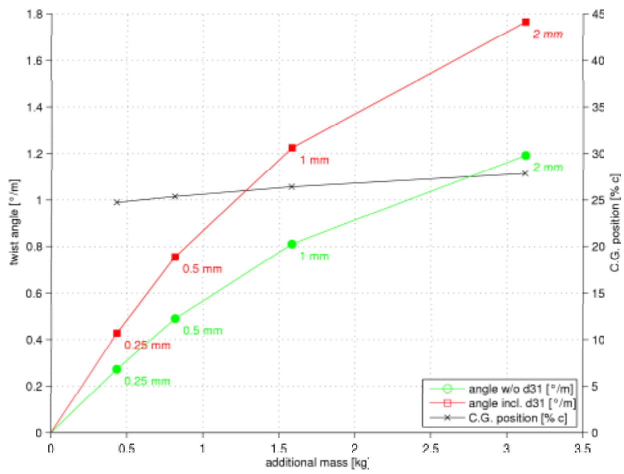


Fig. 4 : Comparison of twist performance, additional mass and center of gravity for varying piezo thickness of concept 1D

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.

3 AIRFOIL CAMBER

While active twist concepts aim at the variation of lift without affecting pitching moment, airfoil camber may

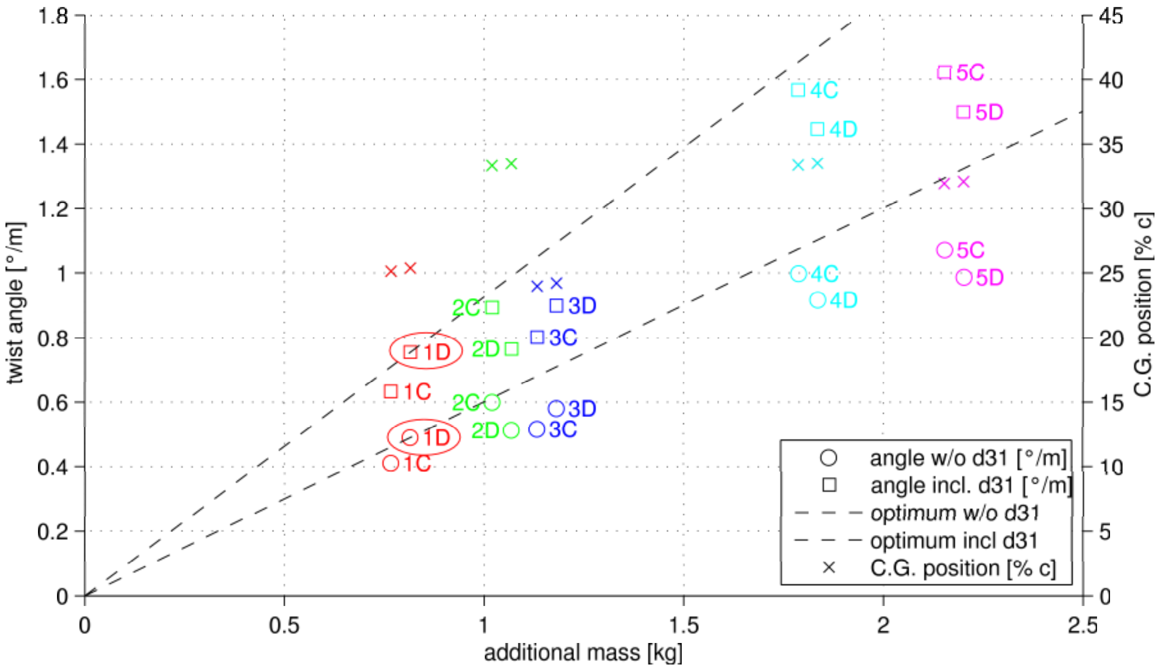


Fig. 3 : Comparison of twist performance, additional mass and center of gravity for different actuator layouts

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 [5, 6]. A continuously deforming leading edge of a blade actuated by electromagnetic drives has been reported by Fink et al. [7].

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 [9]. The corresponding actuation system based on piezoceramic stack actuators is described in [10].

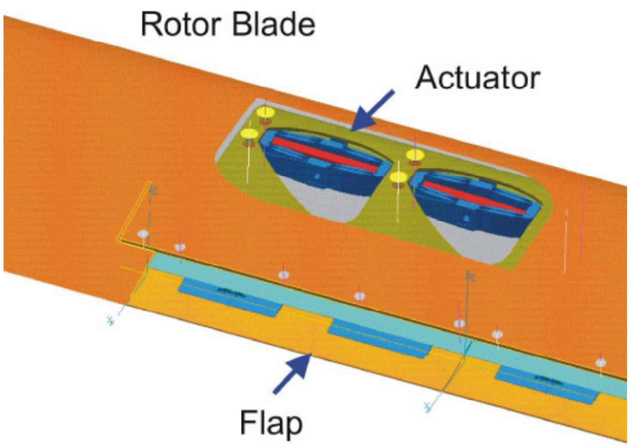


Fig. 5 : Trailing Edge Servo Flap piezoelectric actuation module

3.2 Active Trailing Edge

Similar to the trailing edge servo flap with discrete hinge, continuous blade trailing edge deformation 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 [11], see Figures 13(a) and 13(b), respectively. The Active Trailing Edge actuator

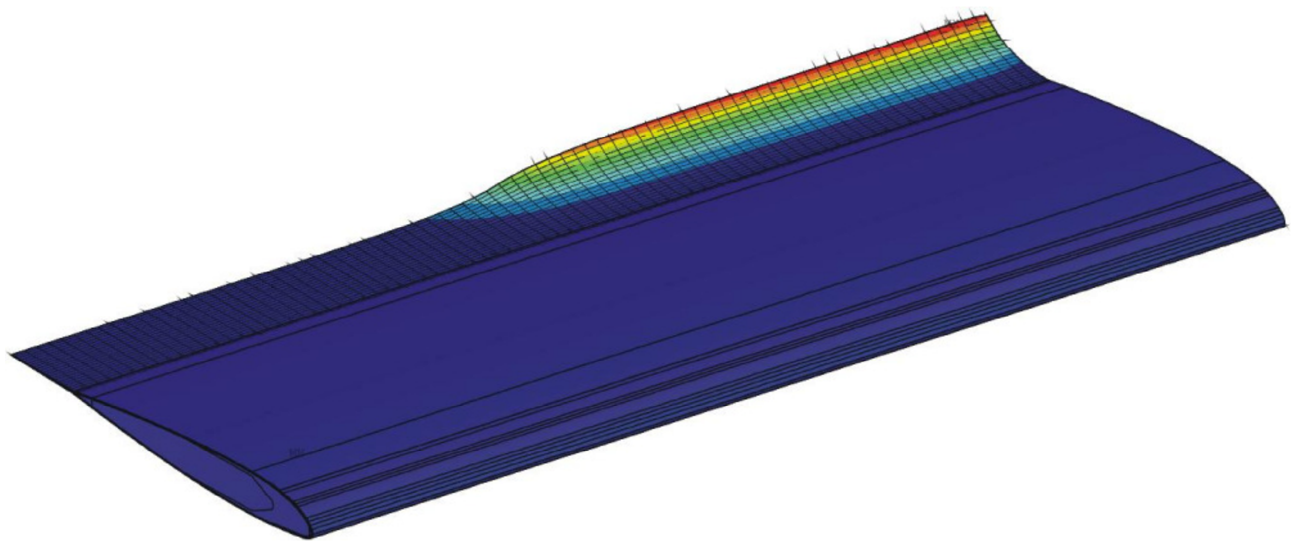


Fig. 6 : Active Trailing Edge smooth blade shape deformation

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.

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 heliocopter 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 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.

Figure 7 depicts a comparison of different Active Tab and 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 leading 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 piezoceramic 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.

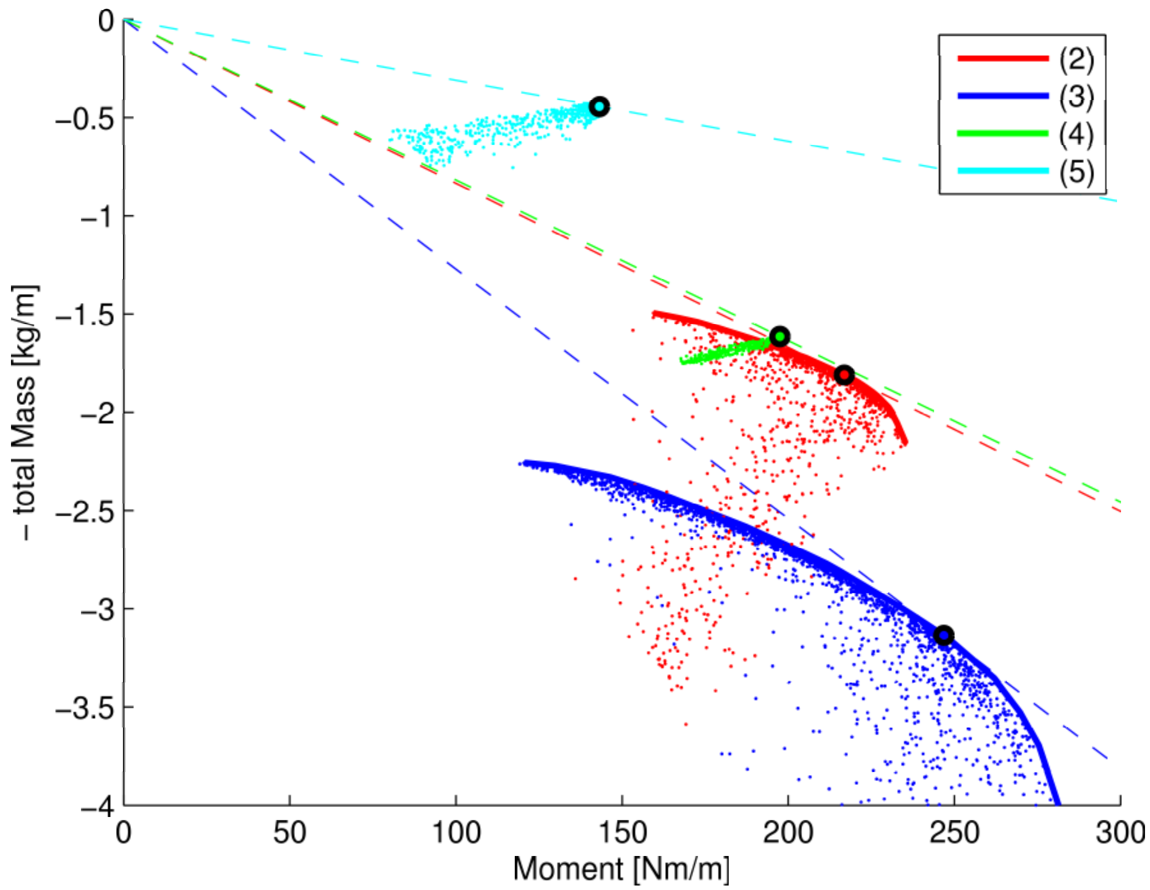


Fig. 7 : Optimization of Active Trailing Edge actuator concerning additional mass versus aerodynamic effectiveness in terms of pitching moment: PARETO fronts and tangents representing best performance ratio

Figure 7 depicts PARETO fronts for 4 different designs. Design (2) corresponds to an Active Tab while (3), (4) and (5) represent different Ative Trailing Edge layouts. Each PARETO front represents the boundary of best possible designs in compliance with given constraints and design degrees-of-freedom. The tangent from (0; 0) to each PARETO front yields the best possible performance ratio of pitching moment to additional mass. It is seen that the performance ratio in terms of moment per mass is best for design (5). With increasing moment capabilities the performance ratio deteriorates significantly for designs (4), (2) and (3).

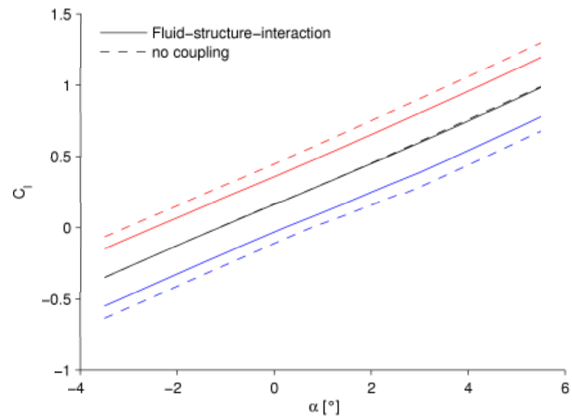
In addition, applying the results depicted in Fig. 7 for actuator optimization, it must be considered that the final trade-off between pitching moment and additional mass must take into account overal blade design and rotordynamic effectiveness.

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.

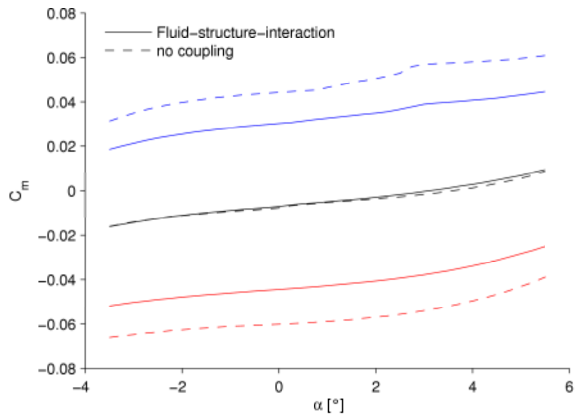
3.2.2 Active Reflexed Skeleton Line

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.



(a) $C_l(\alpha)$



(b) $C_m(\alpha)$

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

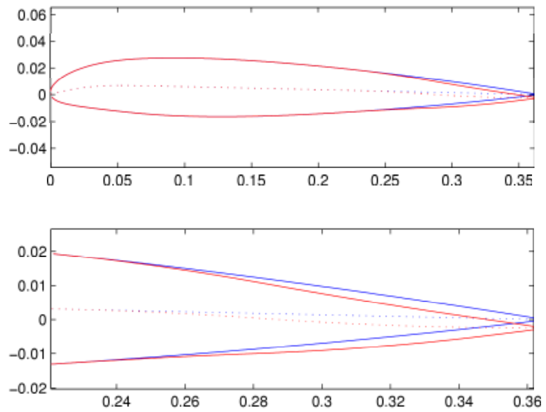
An example layout is depicted in Fig. 9(a). The total chord of the Active Trailing Edge is $141mm \approx 39\%$ chord whith $125mm \approx 34\%$ chord piezo. The active reflexed skeleton line is achieved by deflecting the Active Trailing Edge in one direction at its upstream root while the downstream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

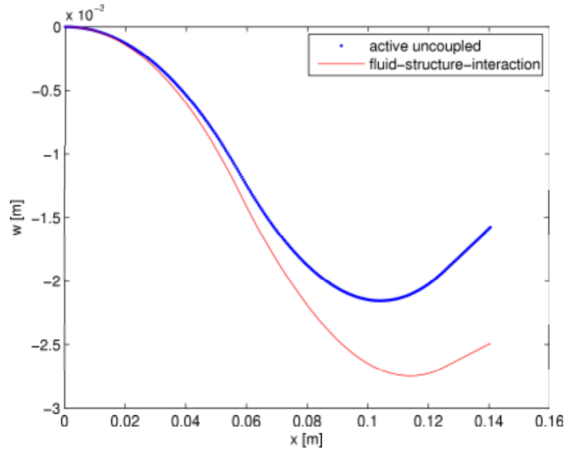
Design studies show that effectiveness concerning lift coefficient may be doubled in comparison to the example actuator design presented above, e.g. $\Delta C_l \approx 0.28$ corresponding to a change of angle of attack of a flat plate $\Delta\alpha > 2.5^o$ if moderate influence on pitching moment coefficient 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.



(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

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 applied to advanced planforms featuring varying blade chord and small airfoil thickness, e.g. a parabolic blade tip as depicted in Fig. 10.

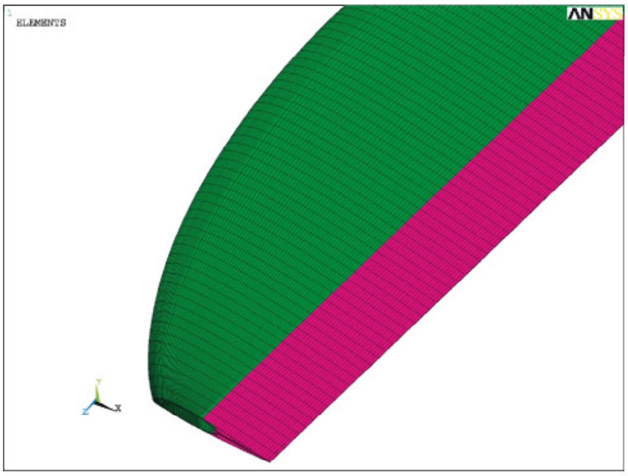


Fig. 10 : Active Trailing Edge integrated into blade tip

In addition to these integration issues, spanwise segmented differential actuation of Active Tab or Active Trailing Edge may be easily realized without aerodynamic penalty resulting from gaps and kinks as discussed above, see Fig. 6. The benefit of segmented trailing edge actuation has been demonstrated by several authors, e.g. FRIEDMANN [12]. Especially in the blade tip region, spanwise segmented inversely or differentially actuated devices bear the potential of multi-purpose application for vibration, performance enhancement and noise reduction.

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 [13], e.g. Macro Fibre Composite (MFC) actuators. Figure 13(a) depicts an Active Tab demonstrator employing a bending actuator built from MFC patches.

MFC actuators feature easy handling and promise high strain actuation performance as well as robustness with respect to large passive strain. The main disadvantages of MFC actuators are the high driving voltages of $-500V < U < +1500V$ in combination with limited actuator thickness due to interdigitated electrode technology. Unfortunately, the availability of standard power electronics components is limited to voltages in the range of $200 \approx 600V$. As discussed in a previous section, the piezoceramic actuator thickness required for full-scale blade twist is expected to be $> 0.5mm$. Because this is beyond what can be realized with single MFC actuators, several actuators may be laminated [14] or alternative piezo actuator technologies have to be developed.

Fig. 11 : Array of piezoceramic stacks for multi-morph bending actuator

Figure 11 depicts a 5x3x2 array manufactured from 15x24x0.4mm^3 NOLIAC piezoceramic stack actuators developed for the Active Trailing Edge. As can be seen from Fig. 12 the active deflection at full operating voltage $U_{pp} = 180V$ is approximately $\pm 2.3mm$.

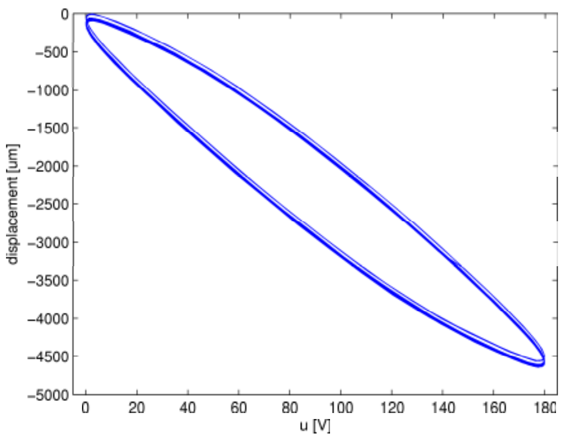
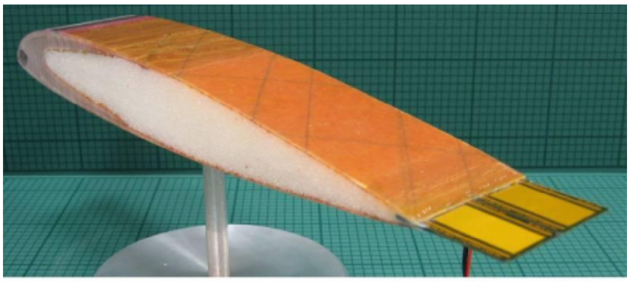


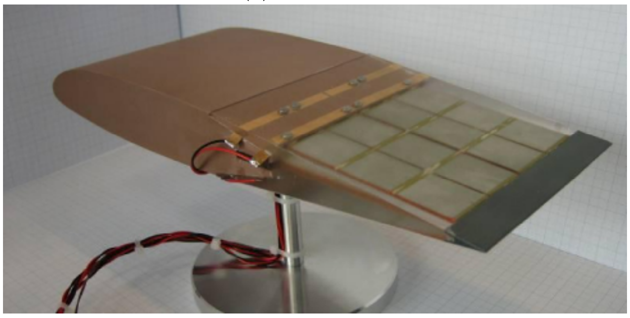
Fig. 12 : Active Trailing Edge bending actuator performance in terms of tip displacement as function of driving voltage

Figure 13(b) 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.



(a) Active Tab



(b) Active Trailing Edge

Fig. 13 : Actuation concept demonstrators

5 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 performance, 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 is still pending.

For this reason, future development efforts will increasingly focus on reliability issues including redundancy concepts, integration, manufacturing and cost. Furthermore, the aerospace supplier base in the field of piezoceramic actuators has to be further developed.

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