STRUCTURAL DESIGN AND OPTIMIZATION OF THE INTEGRATED ACTIVE TRAILING EDGE CONCEPT FOR A HELICOPTER ROTOR BLADE

Elif Ahci, Rupert Pfaller
Eurocopter GmbH, Willy-Messerschmidt Straße, 81663 Munich, Germany
elif.ahci@eurocopter.com; rupert.pfaller@eurocopter.com

Keywords: Active trailing edge, optimization, piezo ceramic actuation, adaptive rotor, active blade, shape morphing, elastic flap

ECD-0162-07-PUB

ABSTRACT

Active Trailing Edge (ATE) concept is studied in detail in this paper.
An integrated active section is defined for the trailing edge of the rotor blade and finally optimized to achieve the strength requirements and the maximum aerodynamic efficiency. Similarly, the integration details, i.e. the construction of the transition section between the active and passive parts (i.e. the sections with- and without piezo actuators) of the blade are discussed.
A structural optimization study coupled with the aerodynamic requirements is performed in order to determine the geometry and the stiffness of the bender with attached piezo ceramic actuators. Mass, stiffness and maximum trailing edge deflection are defined as target functions. Several constraints were defined by rotor dynamics and active material properties.
The results representing the influence of the piezo thickness on aerodynamic performance and the benefits of the variable thickness are presented. The highest efficiency has been obtained for variable thickness of bender and piezo in chordwise direction. However, it is technologically quite difficult to manufacture piezo ceramic actuators with variable thickness.
Piezo ceramic materials are quite brittle, the allowable tensile stress is very low and the Young's modulus range is quite limited. Therefore, to reduce the normal strains transferred to the piezo ceramic material, the trailing edge geometry is further modified. It has been determined that it is mandatory to introduce cutouts into the blade structure in chordwise direction throughout the span.
Finally, it has been understood that the stiffness of the filling material has a remarkable effect on the trailing edge deflection and hence on the overall aerodynamic performance. Therefore, it is obligatory to choose a flexible, low modulus material to achieve the required aerodynamic efficiency.

1. INTRODUCTION

The current helicopter design technology was not yet able to completely eliminate the high levels of in-cabin and external noises and vibrations. One of the main sources of noise and vibration is the main rotor, especially in fast forward and descent flight. Recently, several research projects have been launched to develop advanced rotor control systems to address this problem. The main objective of these efforts is on one hand to strengthen the acceptance of the helicopters in civil life and on the other hand, to improve the comfort for the users and the operators.
Individual Blade Control (IBC) technology, as well as the conventional control concepts promises improvements up to certain level. IBC is a state-of-the-art technology for vibration and noise reduction, as well as for reduced power consumption. On-blade actuation mechanisms based on active materials are used for this purpose. The principle of this concept is to minimize the vibrations by actively changing blade pitch during the operation. This technology offers several advantages in weight, power consumption and bandwidth compared to hydraulic control systems.
Eurocopter has been working on different IBC concepts for several years, such as blade root actuation, discrete trailing edge flaps and the integrated active trailing edge concept.
The first IBC demonstrator operated by ECD was the BO 105 helicopter which uses electro-hydraulic blade pitch actuators provided by ZF Luftfahrt-Technik (ZFL) which replaced the pitch links in the rotating frame. The available IBC blade pitch amplitude proved to be sufficient for impressive BVI noise reduction in descent flight [1] and for significant vibration reduction in level flight [2].
Although the electro-hydraulic system of the BO 105 behaved well during the experimental campaign, a promising actuation concept was seen

in piezo-actuated trailing edge flaps for future applications. An experimental EC 145 helicopter serves as a prototype airframe for this concept. Compared to the BO 105, both helicopters use a four bladed main rotor system with a hingeless rotor hub while the EC 145 has an increased maximum take off weight.

The EC 145 main rotor has been used as the basis for the implementation of the flaps. The design of the blade was modified to integrate the active trailing edge flaps. The flap system consists of three identical units. The trailing edge of the blade was cut and filler foam was used as a support medium between the upper and lower blade skin together with the carbon fiber box. The box is open at the rear side. After inserting the units into the blade, all parts are screwed and sealed to ensure the stiffness and strength requirements of the blade, as well as the protection of the flap actuation system against humidity (Fig. 1).

Fig. 1: Integration of flap modules into the rotor blade structure at the trailing edge

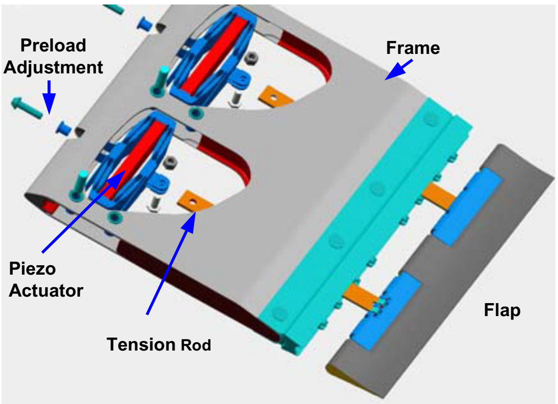

Fig. 2: Flap unit assembly with tension rods, flaps, piezo actuators, actuator frames and housing

One pair of piezoelectric actuators located at a most forward chordwise position act via tension rods attached to the flaps (Fig. 2).

The most important design targets were the high structural stiffness, low friction of the bearings, mechanical stability of the modules and finally the low mass of the unit, especially of the flap.

The full scale rotor system was tested first on whirl tower in passive and active modes. Afterwards, detailed flight test campaign has started. The official first flight with discrete active trailing edge flaps took place in September 2005. The airborne demonstrator is shown in Fig. 3. Since then, many promising flight tests were accomplished [3].

Fig. 3: First flight with active trailing edge flaps

Early wind tunnel and following flight tests have shown a noticeable reduction in vibration levels by the use of discrete flaps at the trailing edge. However, the mechanics of the discrete trailing edge flaps is quite complex. The piezo actuators are placed close to the leading edge of the rotor blade. Thus, the deformations of the actuators must be transmitted by means of appropriate mechanical elements to the trailing edge which makes the design more complicated. The wear of bearings, aerodynamic sealing and the discontinuity in the blade profile are the other difficulties arising with discrete flaps and cause inconveniences in terms of serial production.

A further step towards the greater simplicity and the robustness is the introduction of the active elements locally into the blade structure rather than the application of discrete flaps.

2. ACTIVE TRAILING EDGE CONCEPT

The so-called Active Trailing Edge (ATE) concept is based on direct integration of the smart material actuation into the rotor blade structure to accomplish a morphing cross section. This concept was brought to life by introducing a multi-morph bender into the blade structure (Fig. 4).

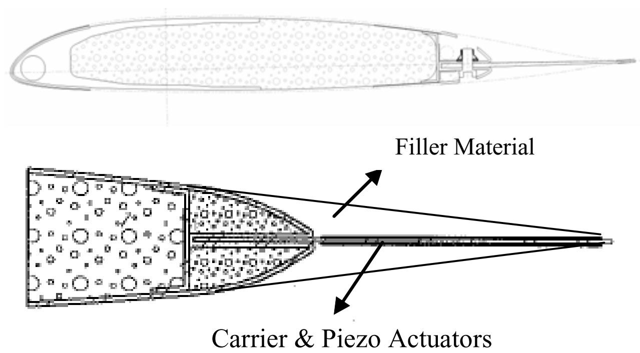

Fig. 4: Rotor blade with integrated active trailing edge (ATE) and interface to passive blade structure including the filler material and multi-morph bender

The bender is made up of piezo ceramic actuators attached to a fiber reinforced composite carrier laminate. The carrier is an electrically isolated; glass fiber reinforced composite plate and is placed in the center of the bender (Fig. 4). The piezo ceramic actuators can be attached on one or both sides of the carrier. The piezo ceramic is stretched by the introduction of electrical voltage. A varying elongation is obtained by applying the piezos on both sides of the carrier, i.e. upper and lower. From this elongation, the intended bending of the trailing edge arises.

A flexible, foam type material fills the gap between the bender and the aerodynamic profile and supports the airfoil shape (Fig. 4). The resultant active module is integrated at the end into the blade structure without changing the aerodynamic profile.

Similar to the discrete trailing edge flaps, the ATE works with the principle which is based on aeroelastic twisting of the blade using the servo effect, i.e. the rotor blade twists due to the change in the aerodynamic pitching moment.

The most challenging part of ATE concept is to design the active part of the structure for load carrying capabilities and active deformation simultaneously. The active section of the blade should be as flexible as possible to achieve high trailing edge deflections and high aerodynamic efficiency. On the other hand, certain amount of stiffness is necessary to carry the aerodynamic forces and operational loads. At this point, multidisciplinary cooperation of such areas as aerodynamics, structural dynamics, flight mechanics, actuator technology and stress is essential for an optimum design.

The piezo ceramic actuators are to be mounted close to the trailing edge of the blade profile. However, the tensile stresses and strains due to centrifugal force, flapping and lead-lag moments are relatively high at this part of the blade. Thus, the composite bender with attached piezo actuators has to withstand these loads. Otherwise, the bender has to be protected from the effect of the given loads. However, the ceramic piezo material can hardly withstand such high tensile stresses. Therefore, it is mandatory to reduce these strains by introducing modifications into the blade structure.

The blade trailing edge is cut into several segments to reduce the normal strains especially due to centrifugal force (Fig. 5). This modification makes it possible to use the piezo ceramic materials as bending actuators at the trailing edge. Without this constructive improvement, the piezo ceramic would fail immediately due to the strains arising only from the centrifugal load. Thus, an active trailing edge would be impossible.

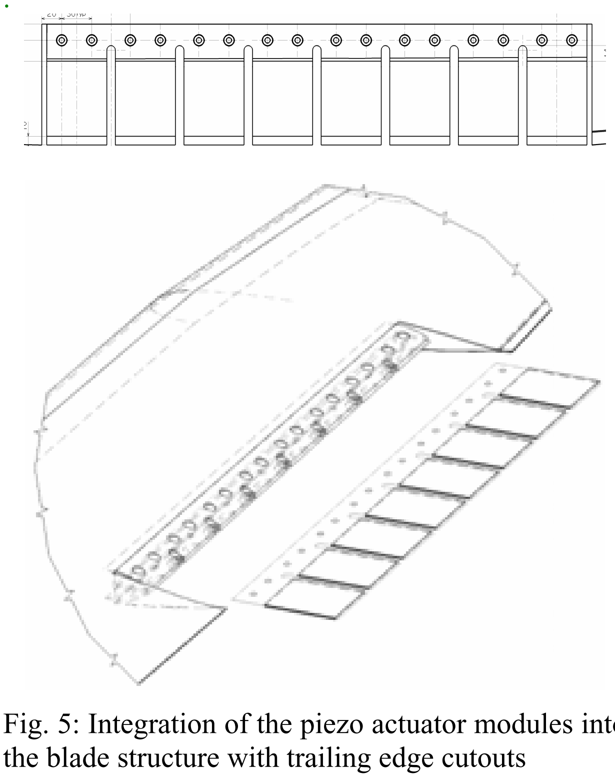

Fig. 5: Integration of the piezo actuator modules into the blade structure with trailing edge cutouts

The adaptive rotor blade with ATE and cutouts must accomplish the requirements of the conventional blade without active elements. The modified active part of the blade should be redesigned in such a way

that the center of gravity should lie as close as possible to the 25% chord line. Any change in the global stiffness and weight distribution of the blade changes the dynamic characteristics of the blade and introduces additional dynamic loads.
The lay-out of the active trailing edge with cutouts in chordwise and spanwise directions is defined by a parametric study. Then, a structural optimization is performed for the active cross section to define the filler material characteristics and the geometry of the bender.

3. ANALYTICAL MODEL

3.1. Parametric Investigations

The problem of high effective normal strains on the piezo materials was solved by allocating the trailing edge into segments. By this way, only part of the strains will be transmitted to the active trailing edge and thereby to the piezo ceramic material. By the optimal definition of the width of the individual segments, the depth of the cutouts and the type of the bonding (e.g. glued, bolted), the strains on the piezo ceramic actuators can be reduced considerably.
The influence of the segment width, interface length and stiffness were investigated by means of a parametric model. The model is based on a shear lag theory with two flanges and a load introduction in the longitudinal direction as shown in Fig. 6. One half of this symmetrical model is used to get the effects of the mentioned parameters.

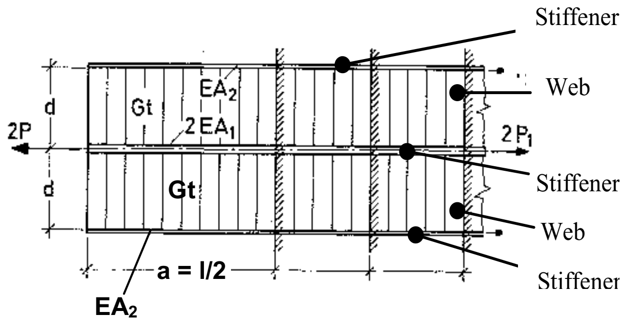

Fig. 6: Analytical symmetrical shear lag model representing the strain transfer from the rotor blade to the piezo actuators [4]

The principle sketch of the active section with piezo actuators (stiffness of E_2A_2) and the transition section (shear stiffness of Gt) between the piezos and the passive part is shown in Fig. 7. The rear part of the blade where high strains occur has the stiffness E_1A_1. Comparison of the Fig. 6 and Fig. 7 demonstrates the simplifications made. So, with this simple model the influence of the following parameters are investigated:

- Stiffness of E_2A_2 of the piezo area together with carrier
- Shear stiffness Gt of the transition area between the piezos and the blade
- Cutout depth, i.e. interface length, between the piezo actuators and the passive blade section (Fig. 8)
- Width of piezo segment (Fig. 9)

The influence of cutout length in chordwise direction (i.e. interface length between active and passive parts of the blade) is given in Fig. 8. It is obvious that the transferred strain is reduced considerably even with relatively small cutout length (“d”). Similarly, the effect of piezo actuator width (“l”) is presented in Fig. 9. It is evident that the resultant strain in piezo ceramic actuators reduces with decreasing segment width.

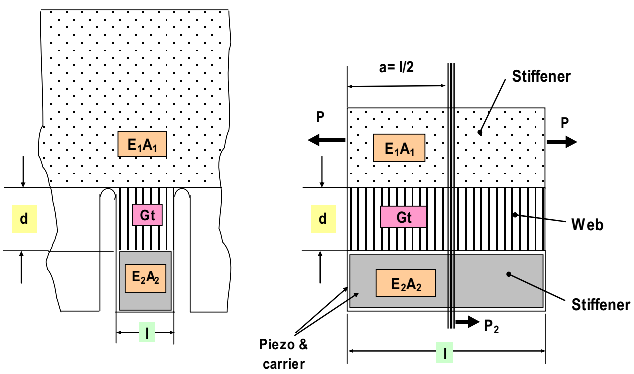

Fig. 7: Adaptation of the analytical symmetrical model to the real rotor blade structure

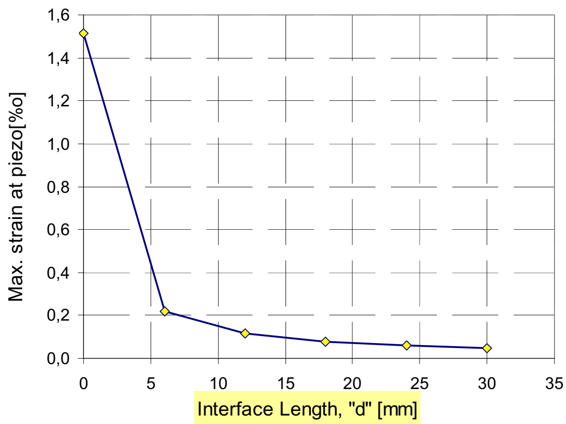

Fig. 8: Influence of the interface length between active and passive parts of the blade on resultant strain at the piezos

Fig. 9: Influence of the segment, i.e. piezo, width on the resultant strains at piezo actuators

The changing piezo/segment width produces contrary effects for the strain resulting at the piezo actuators, as it is shown in Fig. 10. So, with a reduction of the width, the strain transferred from the blade to the piezos will be reduced, but the strains caused by centrifugal forces increases. Both effects added show a flat optimum for a width between 60 and 120 mm.

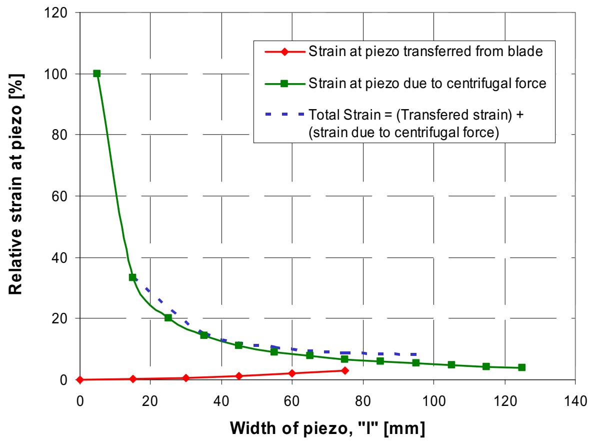

Fig. 10: Variation of the total strain at piezos with respect to piezo width (total strain is the summation of the transferred strains from the blade and the strains due to centrifugal force)

The stiffness parameter of the blade (E_1A_1) is more or less defined by global blade requirements because the stiffness of the original blade should be kept. For the original design the strains in different chordwise positions throughout the spanwise length for the flap area are calculated analytically as shown in Fig. 11.
The comparison of Fig. 8 and Fig. 11 shows that, segmenting the blade trailing edge reduces the normal strains from 2.5 %o down to 0.2 %o without the consideration of the inertial forces resulting from additional piezo weight. When the weight of piezo is taken into account, normal strain increases again. But at the end a remarkable reduction in resultant strain at piezos is achieved and by this way it is shown that the ATE with certain modifications is an useable concept.

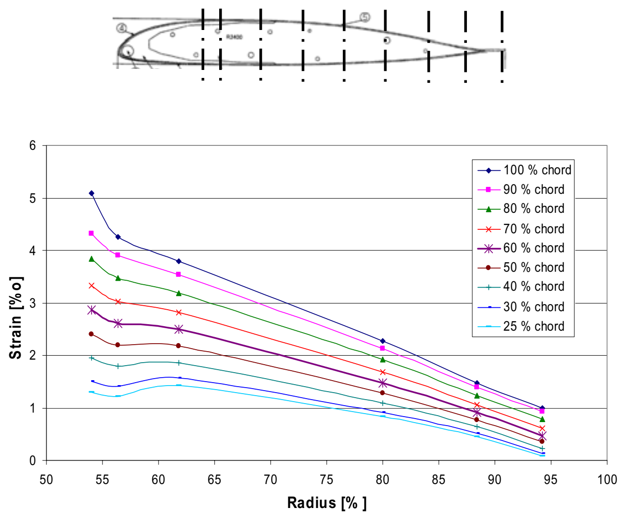

Fig. 11 : Resultant strains on a conventional blade skin without active elements along the radius for different relative cordwise positions

3.2. Modeling of the Active Trailing Edge by Field Transfer Matrix Method

In order to be able to compare the deflection and thus the aerodynamic effectiveness of different actuator concepts objectively, a theoretical model representing the proposed concept is necessary. This model can also be used to determine the arising deformations and the aerodynamic effectiveness for a given geometry.
The theoretical representation of the blade cross section with an active trailing edge is accomplished by using the field transfer matrix method. Afterwards, the transfer matrix procedure is implemented into a structural optimization routine. The transfer matrix formulation is adapted to a FORTRAN program for this purpose. Consequently, the best possible and accurate solution was determined for the active blade structure to achieve the strength requirements and the maximum trailing edge deflection. The detailed information about the field transfer matrix methodology can be found in [5] and [6].
During the integration of a possible actuator concept into the rotor blade structure several boundary conditions are to be considered, which limit noticeably the spectrum of the possibilities. Most importantly, the existing aerodynamic profile of the

rotor blade is not to be changed. Moreover, the active section has to be brought into the rear part of the blade cross section, i.e. close to the trailing edge, due to aerodynamic requirements.
The placement of the piezo actuators along the chordwise and spanwise directions are defined by a shear lag model as explained in the previous chapter. It is determined that the connection to the passive part should be a stiff connection to protect the ATE from large strains to prevent the losses due to the possible deflections with a soft interface. Thus, only the actively deformable part of the rotor blade section up to the connection to the passive part in chordwise direction is modeled by transfer matrix method. The transition from the passive to the active part is modeled as fixed restraint and similarly, the right end, i.e. the trailing edge, is represented as free restraint. Fig. 12 shows the part of a rotor blade for which the active trailing edge was modeled by field transfer matrices. The geometry selected for the transfer matrix procedure is presented on top of the Fig. 12.
For each transfer section a constant thickness is assumed which is not a pre-condition for this method but nevertheless selected for a simpler conversion. However, in order to be able to illustrate the curved blade profile with sufficient accuracy, a large number of transfer sections with constant individual lengths are selected.

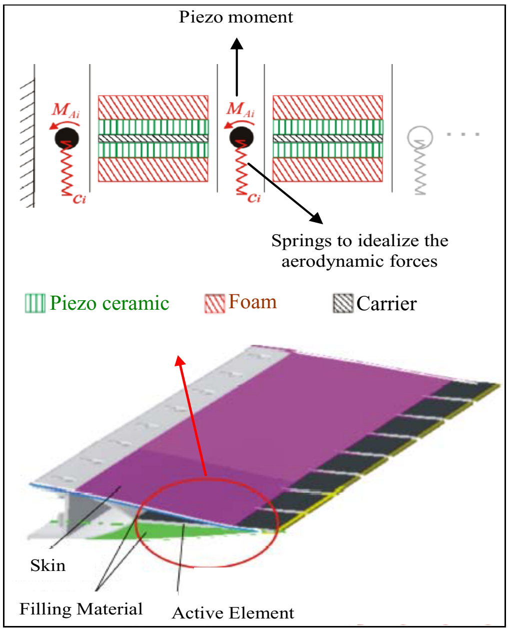

Fig. 12: Conversion of the active section of the blade structure to an analytic model via transfer matrix method

Each transfer section is assumed to have a symmetric structural lay-up. The bending stiffnesses have been determined accordingly. The influence of the shear stiffness on the deformation is assumed to be negligible due to the small height to length ratio of the representative beams.
The aerodynamic flow around the blade profile has a considerable effect on the entire rotor blade forces. For the case of the deflected trailing edge, resetting aerodynamic forces arise and they bend the trailing edge in opposite direction. Therefore, the effect of aerodynamic loads should be included in the determination of trailing edge deflections. In order to examine the influence of the aerodynamic forces on the behavior of the actuator, two discrete aerodynamic pressure distributions were defined for the rotor blade. Since the aerodynamic forces are dependent to the trailing edge deflection, effective forces are to be computed repetitively for each value of the trailing edge deflection. In order to avoid this effort, a linear relation between the trailing edge deflection and the aerodynamic pressure distribution is assumed for small deflections. The computed aerodynamic forces are presented by means of elastic springs in the transfer matrix formulation. The distributions were formed for upwards and downwards trailing edge deflections separately.
Finally, the unknown quantities for each transfer section and at last the maximum trailing edge deflections are determined by using the field transfer matrix method. But the value of the trailing edge deflection does not directly determine the resultant aerodynamic effectiveness of the active section. Critical for this effectiveness is not only the maximum possible trailing edge deflection but more significantly the length of the deformable active part of the blade section. Therefore, in order to optimize the active section in terms of aerodynamic efficiency, a simplified model is defined. In this model the active trailing edge is represented as a discrete flap at the end of a blade profile. Then, the aerodynamic moment coefficient has been defined for this simplified model. This model is based on the principles defined for infinite span wings with flaps [7].

4. OPTIMIZATION

The theoretical modeling of the active blade cross section is done by the field transfer matrix method as described in the previous chapter. This model is then implemented into the optimization routine. For this purpose the procedure is converted into a FORTRAN subroutine. The objective functions, i.e. aerodynamic pressure constant and trailing edge deflection are determined with the help of this subroutine for the given values of optimization parameters.

Besides the theoretical model, the constraints are formulated for the optimization of the active part. The blade outer contour and strength limitations of the used materials are defined as the constraints. The optimization variables (i.e. design variables) are varied until a minimum or a maximum value for the objective function is reached. Fig. 13 shows the general operational sequence of the optimization routine graphically.

The task of the optimization is carried out by a numeric procedure. The required procedure is taken from the software library of the Numerical Algorithms Group (NAG). The NAG source (www.nag.com) offers an overview of the actual programs and modules for the solution of mathematical problems. With the help of detailed documentation, the available modules can be used comfortably.

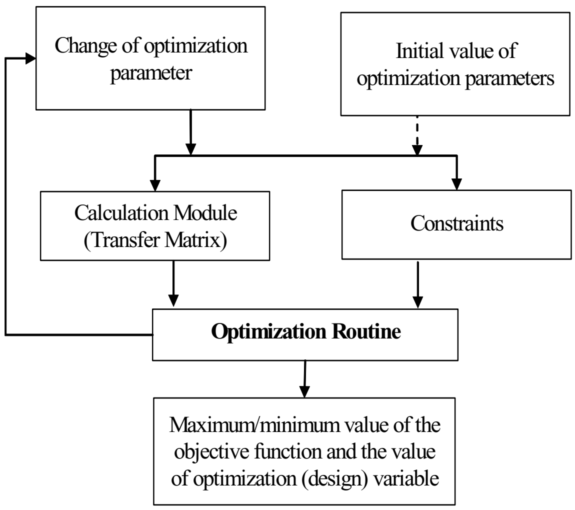

Fig. 13: Graphical representation of the general operational sequence of the optimization routine

The thickness and the stiffness of the carrier laminate, ceramic piezo actuators, filler material and the outer skin contribute substantially to the effectiveness of the active trailing edge. On one hand, a certain minimum bending stiffness has to be achieved at the trailing edge (i.e. passive tip) to withstand the outside forces. On the other hand, the active structure should be as flexible as possible in order to obtain large deflections at the trailing edge. Optimization routine is used to identify the influence of these parameters on the trailing edge deflection and aerodynamic efficiency. The effect of each parameter is investigated individually and presented in the following chapters.

4.1. Effect of the Filler Material

The wall thicknesses of the carrier, piezo ceramic actuators and filler foam are selected as optimization variables (Fig. 4). The elastic modulus of the carrier and the piezo ceramics are accepted as constants. Then, these values are varied to determine the resultant trailing edge deflections with respect to the filler material stiffness. The upper and lower limits of the carrier, piezo and filler thicknesses are defined as the constraints. Additionally, the blade should keep its defined outer contour at the undeformed state. Thus, a relation between the blade outer contour and the carrier, piezo, filler material thicknesses is defined as another constraint. Lastly, the strength limits of the piezo ceramic material is identified as the final constraint.

Computations are performed for two different load cases. In the first case, the effect of aerodynamic loads is not considered. In the second case, the aerodynamic loads are included in the computation.

The modulus of elasticity of the filler foam is varied from 0 to 50 N/mm^2 and in each case the maximum trailing edge deflection as well as the optimal piezo lay-out (i.e. thickness distribution along the chordwise direction) was determined.

The effect of the foam stiffness on trailing edge deflection is presented in Fig. 14 for two load cases, with and without the aerodynamic forces.

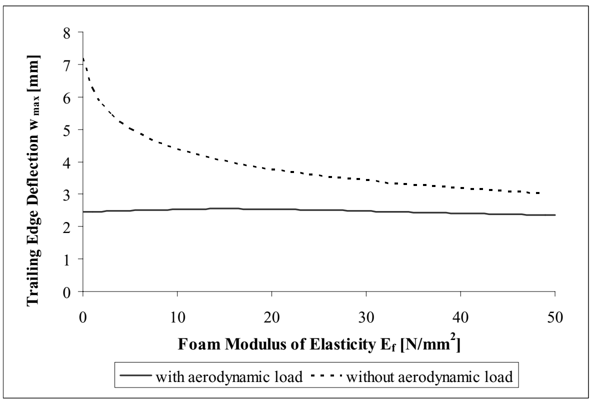

Fig. 14: Influence of the modulus of elasticity of the filler material on the trailing edge deflections (with and without aerodynamic forces)

When the effect of resetting aerodynamic forces are not considered, the highest trailing edge deflection can be obtained with the lowest possible modulus of elasticity of the foam. As the modulus of elasticity increases, i.e. transition to more stiff or inflexible foam materials, the maximum attainable deflection is reduced.

It is obvious that the aerodynamic loads have a significant influence on the resulting trailing edge deflection. The loss of efficiency as a consequence of the aerodynamic forces can be seen clearly in Fig. 14, especially for the lower foam stiffnesses.

The observed losses within the range of smaller modulus values shows up that the previous requirement for the foam with elastic modulus as low as possible is not valid anymore. These losses arise basically due to the insufficient stiffness of the passive tip with extreme soft filler material. Modulus of elasticity of approximately 15 N/mm^2 would be the optimal value to achieve high trailing edge deflections under the effect of aerodynamic loads (Fig. 15).

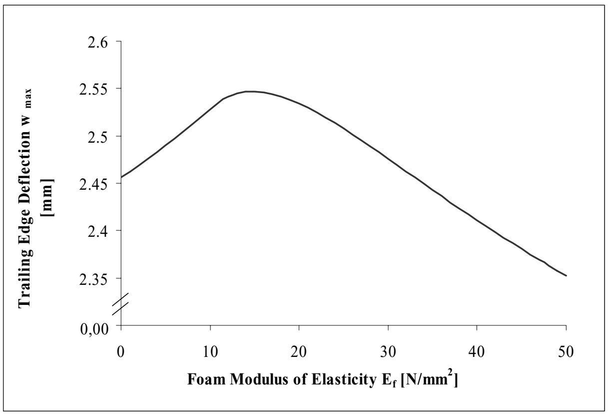

Fig. 15: Maximum deflection of the trailing edge under the effect of aerodynamic load

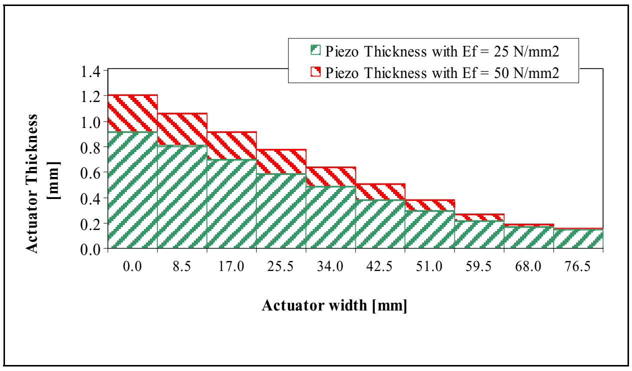

Fig. 16: Optimized layer thicknesses for the piezo ceramic actuator without aerodynamic forces

The optimal thickness distribution of the piezo ceramics along the chordwise direction is presented in Fig. 16. A tapered form, i.e. gradually changing thickness of the piezo actuators along the chordwise direction, is determined as the optimal lay-out which results in highest trailing edge deflection. High bending stiffness is necessary at the restraint in order to be able to withstand high blade loads and accordingly, higher piezo thicknesses results at this part. At the trailing edge however, relatively low bending stiffness is required to achieve higher deflections, thus the thickness of the piezo actuators lowers noticeably too.

The thickness distribution of the piezos together with the carrier along the chorwise direction is determined again for the lower values of the elastic modulus (Fig. 17). For the modulus of elasticity of 0 N/mm^2, a tapered carrier laminate with thickness of 1.225 mm at the restraint and 0.5 mm at the free end of the actuator is calculated. This behavior can be explained by the effective aerodynamic loads and the given strength limitations of the piezo module.

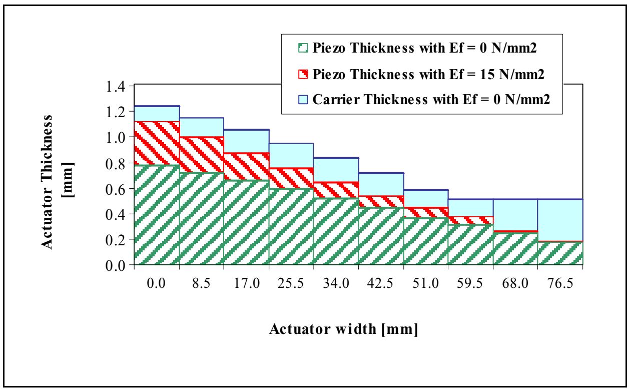

Fig. 17: Optimized layer thicknesses for the piezo ceramic actuator and the carrier with aerodynamic forces

In case of thin layer of carrier laminate which results in low bending stiffness at the trailing edge, the aerodynamic forces could bend the trailing edge backwards. In order to prevent such an effect, a thicker carrier is necessary. On contrary, the required thickness of the carrier laminates decreases with increasing foam stiffness. The required bending stiffness at the passive blade tip can be achieved as well by the contribution of foam stiffness.

As last, the optimization routine is used to determine the optimal value of the aerodynamic moment constant cm$_0$. In contrary to the manageable trailing edge deflections, this aerodynamic characteristic permits a direct statement about the achievable effectiveness of the active structure. The result is presented in Fig. 18. As can be seen in the diagram, for a foam modulus of elasticity of approximately 15 N/mm^2, the aerodynamic moment constant reaches its maximum value. When the results obtained for trailing edge deflection and aerodynamic pressure constant are compared, it can be seen that the maximum deflection and maximum aerodynamic efficiency is reached for approximately the same modulus of elasticity of the foam, i.e. 15 N/mm^2.

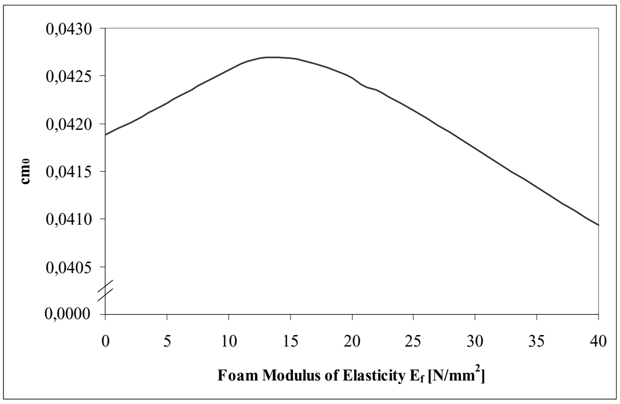

Fig. 18: Distribution of the aerodynamic pressure constant cm_0 with respect to foam modulus of elsticity

4.2. Effect of the Outer Skin

An additional protective layer, i.e. outer skin, is crucial for the protection of the open-cellular foam from the environmental effects.

An additional layer is introduced into the existing transfer matrix model to represent the outer skin to characterize the influence of it on resultant trailing edge deflection. The modulus of elasticity of the skin in chordwise direction and the thickness are investigated throughout the optimization. Three discrete values (0.1 mm, 0.2 mm and 0.5 mm) are considered as outer skin thicknesses.

The effect of outer skin stiffness on the resulting trailing edge deflection for three different thicknesses is presented in Fig. 19 for lower stiffness values.

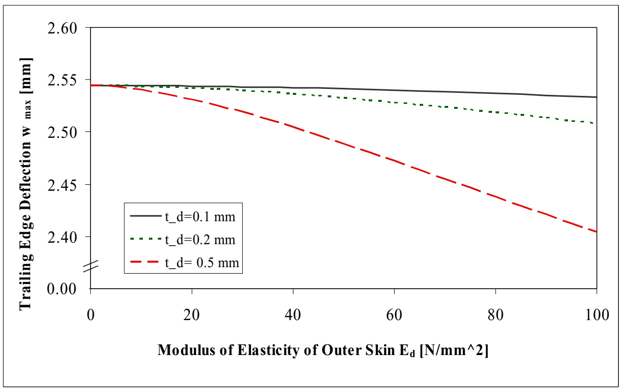

Fig. 19: Effect of the outer skin stiffness on resultant trailing edge deflections (E_d = 0 - 100 N/mm^2)

The results show that the thickness of the additional layer has a considerable influence on the trailing edge deflection. A small change of the outer skin thickness can result in a big difference in the trailing edge deflection. An additional layer causes a relatively considerable increase in the bending stiffness of the active part due to the comparatively large distance to the blade middle axis, even with the lower values of the modulus of elasticity.

For low values of modulus of elasticity, the sensitivity of the trailing edge deflection to the additional layer stiffness is almost negligible up to the thickness values of 0.2 mm. Afterwards the deflection decreases rapidly with increasing modulus of elasticity of the outer skin.

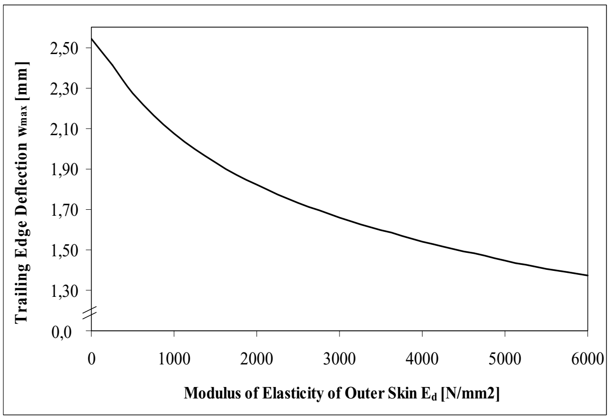

Fig. 20: Maximum trailing edge deflection with respect to outer skin stiffness (E_d = 0 - 6000 N/mm^2)

At this point, further analyses are performed to investigate the effect of higher modulus values on the resulting edge deflection. The thickness of the cover skin is selected as 0.2 mm and the stiffness of the skin is increased from 0 to 6000 N/mm^2. The results are presented in Fig. 20. It is quite apparent from this figure that the increasing chordwise stiffness (i.e. $E_d t_d$) of the outer skin reduces the trailing edge deflection significantly. The high loss in the resultant trailing edge deflection shows that a glass fiber laminate with conventional resin can not be used directly as an additional protective layer on top of the filler material.

It is mandatory to use a thin protection layer with a stiffness as low as possible. Another possibility for an efficient active edge can be the use of filler foams with closed cells and thin coating outside. The problem of sealing with open cell foam can be eliminated by this way and the smooth surface requirement can be achieved at the same time. It is important not to forget that the used filler material and the cover have to withstand the resultant strains due to flight loads.

4.3. Effect of the Carrier Laminate

In this part of the study, the effect of the stiffness and the geometry of the carrier are examined in detail (Fig. 4). Optimal values of the thickness and the modulus of elasticity are determined accordingly.
Initially, the optimization is accomplished for a constant carrier thickness which is varied discretely from 0.1 mm and 0.5 mm.
Fig. 21 shows the dependency of the trailing edge deflection on the carrier stiffness for different thicknesses of the carrier laminate.

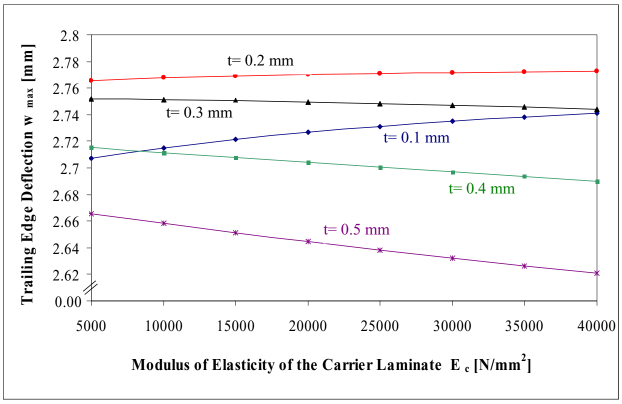

Fig. 21: Maximum trailing edge deflections according to the modulus of elasticity of the carrier for different thicknesses of the carrier laminate

It is interesting to see in Fig. 21 that the trailing edge deflection increases as the modulus of elasticity increases for 0.1 mm laminate thickness. This behavior can be explained by the overall stiffness requirements of the active section which is strongly dependent on the strength limitations of the piezo-ceramics. As mentioned before the active part should be as flexible as possible but should have a certain bending stiffness to withstand aerodynamic and operational loads.
The required bending stiffness of the connection to the blade and of the passive tip can not be achieved for the low carrier stiffness values, if the thickness of the carrier is kept constant. As a consequence, the resultant thickness of the filler material increases, whereby the total bending stiffness rises and achievable trailing edge deflection decreases simultaneously.
As the modulus of elasticity of the carrier laminate increases, the bending stiffness requirements can be fulfilled even with smaller laminate thicknesses which also results in higher trailing edge deflections. A similar but much smaller increase in trailing edge deflection can be observed for the carrier thickness of 0.2 mm.
The other curves representing the results for the carrier thicknesses of 0.3, 0.4 and 0.5 mm show a different behavior. In these cases, the trailing edge deflection decreases with an increasing thickness of the carrier. This behavior can be explained by the increased thickness of the carrier, which yields a higher than necessary thickness for a majority of the carrier laminate. The trailing edge deflection decreases as a result of the higher bending stiffness occurring from the thicker laminate. Thus, the thickest carrier laminate exhibits also the highest loss in the deflection. The value of 0.2 mm has proven itself as optimal thickness, which produce the highest relative deflection at the trailing edge.
Up to now, the attainable thermal pre-stressing by the piezo ceramic actuators and the carrier laminate are accepted as constants, i.e. constant thermal expansion coefficients along the chordwise length. This simplifying assumption is to be modified for more exact computations. By this way, it is possible to obtain higher pre-loading by the thermal stretching of the different materials.
For these investigations, three different laminate configurations are defined as carrier laminate with corresponding chordwise stiffnesses of 19000, 22000, 26000 N/mm^2 and thermal expansion coefficients of 0.2, 0.18 and 0.15*10^{-4} 1/K at the fixed end. The material properties of each laminate configuration have been determined by the classical lamination theory. The modulus of elasticity of the filler material was increased from 0 to 50 N/mm^2 simultaneously. The effect of different laminate configurations on trailing edge deflection is presented in Fig. 22.

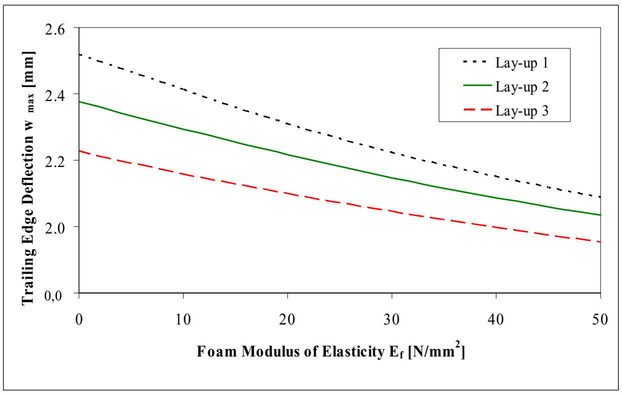

Fig. 22: Trailing edge deflections for different carrier laminate configurations

It is shown that the carrier laminate 1 with the lowest stiffness produces the largest deflections as expected. Laminate configurations 2 and 3 with higher bending stiffnesses compared to laminate 1 result in relatively lower trailing edge deflections. The higher bending stiffness especially at the connection end of the module to the passive blade section helps to reduce the strains transferred from the blade to the piezos and supports the piezo module against the arising deformations. However, at the same time it resists to the trailing edge bending and the attainable deflections decrease automatically.

An interesting behavior is observed when the optimal chordwise thickness variation of the carrier and piezo actuators has been determined. It has been seen that the increasing laminate stiffness decreases the resultant thickness of the piezos (Fig. 23). This behavior can be explained by examining the thermal expansion coefficients of the different carrier laminates.

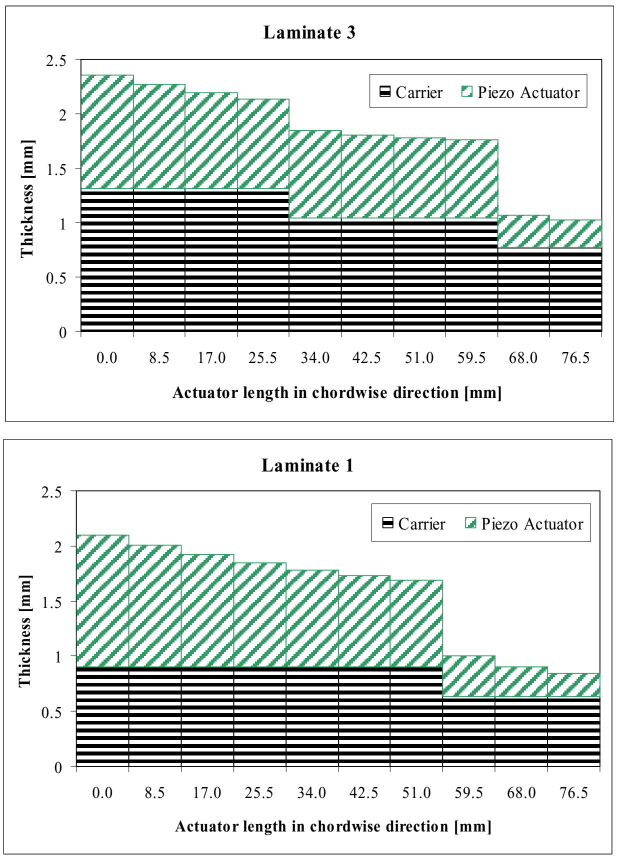

Fig. 23: Optimized layer thicknesses for the active module for different carrier laminate lay-outs

The temperature expansion coefficient (α) is smaller for the stiffer laminate configuration 3 then the one for laminate 1. As the value of α decreases, the achievable pre-straining decreases simultaneously, this yields to a lower strength capability of the piezo ceramic material. Then, the maximum allowed tensile stresses can be achieved easily with small piezo thicknesses. In order to avoid the piezo failure, the thickness of the piezo actuators decreases and that of carrier laminate increases. At last, the resultant trailing edge deflection decreases consequently. The resultant active trailing edge with the increased carrier thickness is then stiff enough to achieve higher deflections. Therefore, the laminate 1 is the optimal configuration which provides the requirements of the bending stiffness and gives the highest trailing edge deflection at the same time.

5. CONCLUSION

It is shown that an acceptable deflection at the blade trailing edge can be achieved with the Active Trailing Edge (ATE) concept. The additional discrete mobile components can be avoided by integrating the piezo ceramic materials into the trailing edge of the rotor blade as a bending actuator. In order to achieve acceptable trailing edge deflections, it is verified that the thickness of the carrier laminate and piezo actuators have to be varied along the chordwise direction. The present work shows that a trailing edge deflection of 2.5 mm is attainable by using an optimized lay-out.

It is demonstrated that the developed method for the modeling and the optimization is an effective method to investigate efficiently the active blade structures with distributed actuating elements. The developed evaluation model via transfer matrix method is a first step for the optimization of active rotor blades or similarly designed wing sections.

In this transfer matrix procedure, the active section is simplified as a symmetrical layered structure (i.e. carrier laminate, piezo ceramic actuators and filler material). The transition between the passive blade structure (i.e. without piezo actuators) and the ATE is idealized as rigid connection. Finally, the substitute model is used in an optimization routine in order to determine the optimal configuration of the active structure.

It is necessary to perform further investigations about the dynamic effects on trailing edge deflections such as consideration of Coriolis forces. Moreover, instead of simplified modeling, more exact representation of the aerodynamic loads improves definitely the estimations regarding the effect of aerodynamic loads on the resulting trailing edge deflections.

6. REFERENCES

[1] Bebesel, M., Roth, D., Pongratz, R., "Reduction of BVI Noise on Ground In-Flight Evaluation of Closed-Loop Controller", *28th European Rotorcraft Forum*, Bristol, UK, September 2002

[2] Roth, D. "Advanced Vibration Reduction by IBC Technology", *30th European Rotorcraft Forum*, Marseille, France, September 2004

[3] Roth, D., Enenkl, B., Dieterich, O., "Active Rotor Control by Flaps for Vibration Reduction: Full scale demonstrator and first flight test results", *32nd European Rotorcraft Forum,* Maastricht, Netherlands Sept. 2006

[4] J. Wiedemann, Leichtbau Bd 1, Bd 2, Springer Verlag 1986

[5] Uhrig, R., "Elastostatik und Elastokinetik in Matritzen-schreibweise" Springer Verlag 1973

[6] Pestel, E. C. and Leckie, F. A., "Matrix Methods in Elastomechanics" NewYork, McGraw-Hill Book Comp. 1963

[7] Schlichting, H. and Truckenbrodt, E., "Aerodynamik des Flugzeugs" Band 2.1, Springer Verlag Berlin/Göttingen/Heildelberg, 1960

ACKNOWLEDGEMENT

This study has been performed in the frame of FRIENDCOPTER project; an EU sixth framework research program. We acknowledge the contribution of the former colleague Mr. Alexander Schuld. Last but not least, we appreciate the collaboration with our project partners from Innovation Works EADS.