ADAPTIVE ROTOR BLADE CONCEPTS
-DIRECT TWIST AND CAMBER VARIATION-

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ABSTRACT

Applying adaptronics to helicopters has a high potential to significantly suppress noise, reduce vibration and increase the overall aerodynamic efficiency. Since the interaction of non-stationary helicopter aerodynamics and elastomechanical structural characteristics of the helicopter blades causes flight envelope limitations, vibration and noise, a good comprehension of the aerodynamics is essential for the development of structural solutions to effectively influence the local airflow conditions and finally develop a structural concept. With respect to these considerations, this paper presents recent investigations on two different structural concepts: the direct twist and the camber variation concept.

The direct twist concept allows to directly control the twist of the helicopter blades by smart adaptive elements and through this to positively influence the main rotor area which is the primary source for helicopter noise and vibration. The concept is based upon the actively controlled tension-torsion-coupling of the structure. For this, an actuator is integrated within a helicopter blade that is made of anisotropic fibre composite material. Driving the actuator results in a local twist of the blade tip, in such a way that the blade can be considered as a torsional actuator. Influencing the blade twist distribution finally results in a higher aerodynamic efficiency. The direct twist concept was analytically modelled using an expanded Vlassov Theory before a proof-of-principle demonstration structure was manufactured. Subsequently, a Mach-scaled Bo105 model rotor blade with an integrated piezoelectric actuator was designed and successfully tested. Next, small scale rotor tests and investigation of thermal loads are planned.

The camber variation concept uses the experiences gained in the design of the direct twist concept to create a rotor blade, that will be able to change the shape of its cross-section in operation. This shape control approach uses material anisotropy (e.g. tension-torsion-coupling) to create a smooth aerodynamic surface and to avoid the airflow disturbances created by the leading or trailing edge flaps, that have already been investigated. First, a structural model was numerically investigated to identify the most influential parameters of this concept. From this model, the two-dimensional surface quality of the deformed rotor blade was extracted as a basis for aerodynamic calculations that are necessary to derive the quantity of deformation needed to successfully delay aerodynamic stall onset. As a next step, a proof-of-principle structural demonstrator is presently being designed.

Both concepts were designed to be activated using a piezoelectric stack-actuator integrated at the blade tip. Since continiuously integrated piezo sheets promise a potential to increase the concepts' performance, thin actuator modules are currently under investigation.

1. INTRODUCTION

Present helicopter research mainly focuses on the improvement of the aerodynamic efficiency and on the reduction of vibrations and acoustic emissions. A direct approach is aiming at the physical sources of these problems. This can be reached by adaptive structural technology.

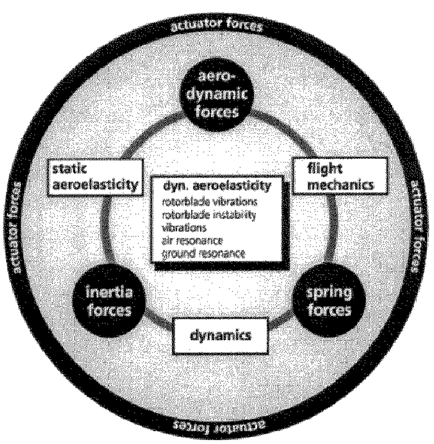

Figure 1: Adaptive aerolastic system

In general, helicopter vibrations and noise exist in all flight cases mainly due to the unsteady working conditions of the blade. This results

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from interactions between the highly non-stationary aerodynamics induced by the rotating rotor blades and special aerodynamic phenomena like the stall effect at the retreating blade and the transonic effect at the advancing blade. All these vibrations are of a highly dynamic nature. The Blade Vortex Interaction (BVI) phenomenon in descent flight is extremely penalising as far as external noise is concerned.

The comprehension of this relationship between the aerodynamic sources and the resulting vibrations and noise is the basis for optimally designed control concepts. Special emphasis is placed on the optimisation of the standard blade control and active control of the blade deflection as the primary tools.

The different kinds of forces which are involved in adaptive rotor dynamics are shown in figure 1. The triangle of forces describes the passive aeroelastic system. In the adaptive aeroelastic system the aerodynamic, inertia and spring forces are influenced by actuator forces or by excited blade deflections.

All aerodynamic effects react highly sensitive to small variations of angle of attack and inflow velocity. Therefore, the main idea of the measures mentioned below, which aims at the reduction of vibrations and acoustic emission, is to dynamically change the blade pitch (twist) or the rotor blade characteristics. Different means are considered for this, e.g. adaptive blade twist, deformable airfoil sections or additional trailing edge flaps.

2. Overview of Conventional and Adaptive Concepts for Vibration and Noise Reductions

In general, control concepts can be divided into two categories (shown in figure 2) depending on where the control forces are introduced. Category I includes all control concepts that are based on blade actuations at the blade root. This can be done by the use of control rods or, alternatively, by designing an adaptive blade root.

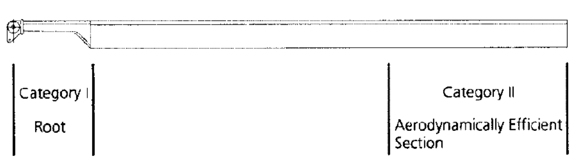

Figure 2: Locations for the use of adaptive material systems

Current research on rotor dynamics has resulted in the design and evaluation of two control concepts to counteract noise and/or vibration, which falls into category I. These concepts can be superimposed on the cyclic blade control deflections: higher harmonic control (HHC) and individual blade control (IBC). These additional mechanisms are two possible approaches to improve the aerodynamic efficiency and to reduce the vibration and noise levels, respectively. HHC is principally based on standard cyclic blade pitch changes using the first rotor harmonic (rotation frequency) to which higher harmonic control motions are added. The angle of attack, the inflow velocity, and the blade deformations can be influenced by these control motions.

IBC is similar to HHC, but the control forces are individually applied to each blade, thus forming a superposition to the global cyclic blade actuation.

By using the control concepts described above, the whole blade is actuated at the root. Aerodynamic reaction is induced after the control forces have travelled through the elastic structure of the blade. As the blade with its high aspect ratio is a highly elastic system, the aerodynamic forces are nonstationary and dependent on the spanwise coordinate and the blade motion. This requires control inputs of a dynamic nature and the evaluation of this system can be achieved only on the basis of global aspects. The real efficiency of this control approach is not clearly assessable.

Category II covers the aerodynamic efficient blade tip section. Here, the concepts aim at the control of the aerodynamic forces which interact with the blade motion.

One example which falls within category II is the *trailing edge flap* (15), which is able to influence lift and aerodynamic moments by flap deflections, is a second concept. However the efficiency of these flap concepts is questionable in respect to long blades with low torsional stiffness. Additionally, blade torsion due to the rudder moments and the additional vortices caused by changes in the lift distribution due to the flap may lead to problems. The trailing edge flap can be interesting for quite rigid blades to create a more adequate lift variation in oder to minimise the vibration and also the noise. It is the so called *Direct Lift Flap Concept* that has been studied especially by ONERA in the co-operation on *Active Blade Concepts* between France and German.

The second concept is the *adaptive twist control*. Investigations on this concept will be described in detail below.

The *adaptive camber variation* investigates active deformations of the cross-section on rotor dynamics. The principle of this actuator concept is presently being developed at the DLR and will be described in detail below.

3. Adaptive Blade Twist

In this concept, the rotor blade twist, especially at the outer part of the rotor, can be achieved by the following actuator principles:

- Torsion caused by a servo-flap (15)
- Torsion caused by 45° orientated tension forces (15),(9),(3),(13),(2)
- Torsion due to torsion-warping-coupling (5)
- Torsion due to torsion-tension-coupling (6),(9)

3.1 Torsion caused by a servo-flap

According to this actuator concept, the flap deflection should produce aerodynamic rudder moments leading to a torsional deflection of the blade. This concept called *servo-flap concept* is more adapted to blades with reduced torsional stiffness. The efficiency of this concept is questionable in respect to the change of the lifting force due to the flap deflection, which counteracts the lifting force caused by the blade twist (figure 4). Additionally, two new vortices caused by the change in the lift distribution due to the flap may lead to new BVI as well as the above mentioned *trailing edge flap*.

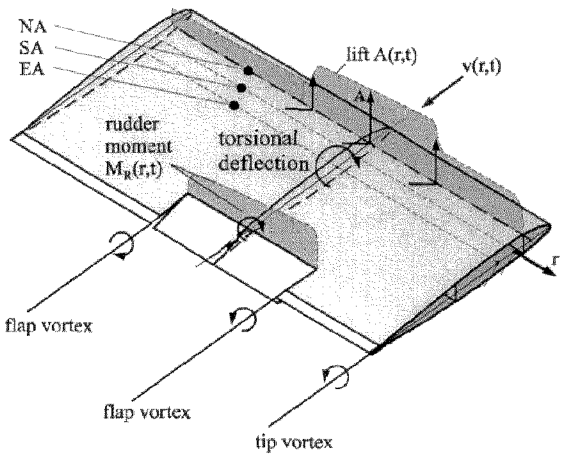

Figure 4: Different approaches by using flaps

A further disadvantage of this concept for using aerodynamic forces is the non-stationary character of the rotor aerodynamics. Constant flap deflections cause non-stationary rudder moments which lead to non-stationary torsional excitation of the rotor blade.

3.2 Torsion caused by tension forces oriented at 45°

In this concept, shown in figure 5, torsional moments caused by tension forces are utilised. Thin-walled actuator materials like piezoceramic plates or active fibers have to be implemented in the skin of the rotor blade to activate it.

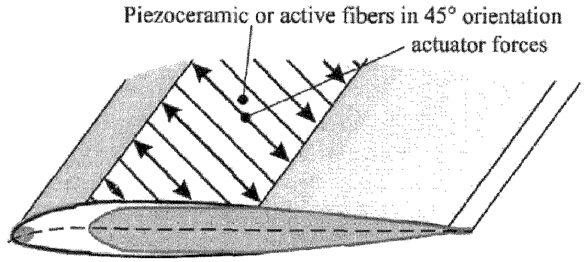

Figure 5: Torsion induced by tension forces

The advantage of this simple concept, that acts in the flux of work, is the good control characteristic. However, the effects of centrifugal forces and the blade flexions have to be taken into account to have access to an efficient design.
One disadvantage of this concept is the insufficient damage tolerance behaviour.

3.3 Torsion due to torsion-warping-coupling

As shown in figure 6, the torsional deformations of the rotor blade are caused by warping forces.

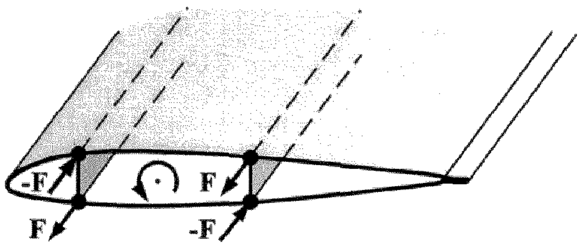

Figure 6: Torsion induced by warping forces

In comparison to the previously mentioned concept, cylindrical actuators, for example piezoelectric elongators (piezo-stacks) can be used to induce warping. It is however necessary to change the geometry of the rotor blade cross section to realise this warping-torsion-coupling. The locally restricted effect of the warping forces, the changes in the geometry, and the installation space of the actuators may cause problems for implementing this concept into a rotor blade.

3.4 Torsion due to torsion-tension-coupling

In general, torsion-tension-coupling is an anisotropic behaviour which appears in structural components. It can be realised by orientated stiffness. The anisotropic material behaviour clearly has to be separated from the anisotropic structure behaviour resulting from structure elements like ribs or stringers.

In this concept anisotropic material behaviour caused by helical winding is illustrated in figure 7.

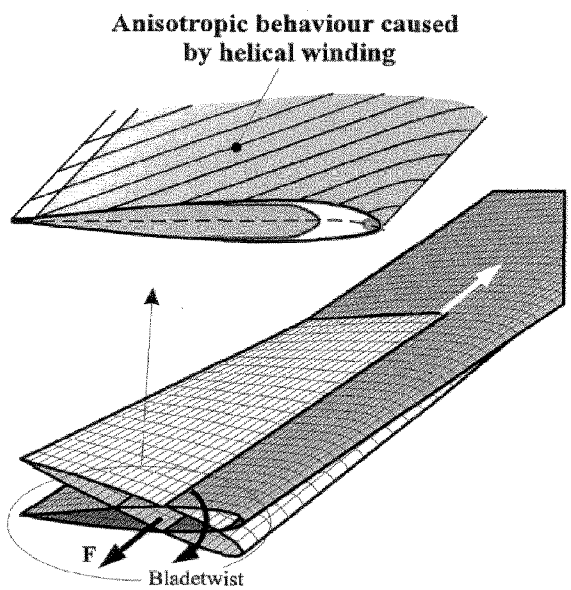

Figure 7: Adaptive blade twist

For practical realisation, cylindrical actuators like piezoelectric elongators (piezo-stacks) can also be used. A disadvantage of this concept is the high spanwise stiffness of the rotor blade spar. Thus, an uncoupling layer between the spar and the skin is needed. An actuator supported at the rotor blade spar generates the axial forces. The principle of this actuator concept is presently being developed at the DLR. (10)-(12)

EXPERIMENTAL INVESTIGATIONS

The experimental investigation comprises three steps.

First, structural investigations were performed based on a representative model in which the active part of the rotor blade is simplified by a thin-walled, tension-torsion-coupled, rectangular beam, that is structurally equivalent to a model rotor blade of the Bo105 with a scaling factor 2.54. The goals of these experiments were to validate the calculations and to gather first experiences with the tension-torsion-coupling and the resulting deformation behaviour. The results are valid for static and dynamic conditions. For the dynamic condition excessive deformations near the blade resonance frequency shall be utilised. Therefore, the actuated blade section has to be properly designed for these preconditions. This has been demonstrated and verified in experiments (7).

In the *second step* the development of a suitable manufacturing technique, the realisation of a simplified rotor blade with tension-torsion-coupling and measurement of the deformation behaviour were investigated.
The technical challenge of the adaptive blade twist concept is the high spanwise stiffness of the rotor blade spar. Thus, an uncoupling layer between the spar and the skin is required. For these experimental investigations the skin of the outer part of three model rotor blades was manufactured of fibre composite material using the above mentioned tension-torsion-coupling effect with different kinds of uncoupling layers between skin and spar.

Blade I: Uncoupling by rubber elements (type a).
Blade II: Uncoupling by rubber elements (type b).
Blade III: Uncoupling by friction.

The simplified cross-section is shown in figure 8.

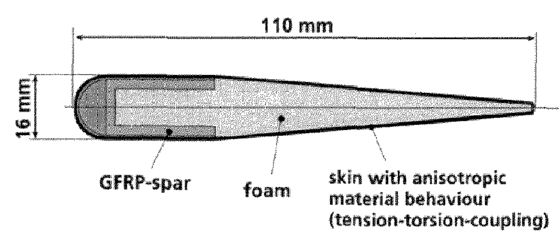

Figure 8: Simplified cross-section.

Equal to the investigation of the boxbeam a hydraulic tension proof machine was used to induce the actuator forces. The twist distribution and the torsional movements at the blade tip were measured for different harmonic tensional excitations between 1 Hz and 25 Hz. The experimental configuration and the results of the experiments are shown in Figure 9a and 9b.

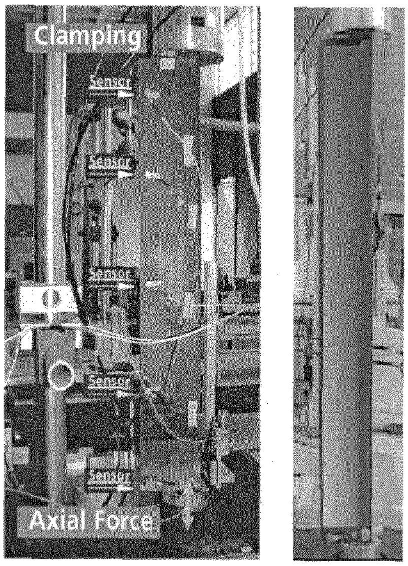

Figure 9a: Experimental configuration
(Blade Segment w. Tension-Torsion-Coupling).

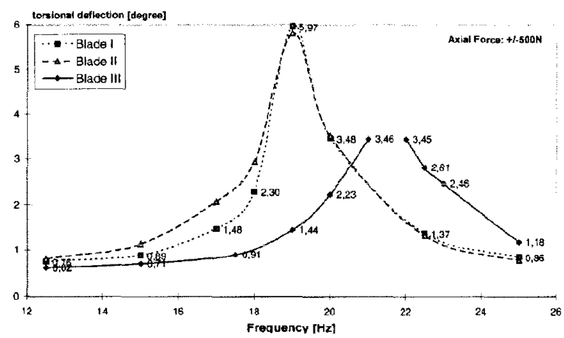

Figure 9b: Results from the dyn. tension test.

The right picture of figure 9a shows of *Blade I* the measured deflections out of plane at 19 Hz. It could be shown that for all uncoupled layers linear twist distributions are excited.

Figure 9b shows the torsional deflection at the blade tip for different excitation frequencies and actuator forces between ±550N. The differences in the torsional resonance frequencies of the three blades are caused by stiffness variations in the structures. Near the resonance frequencies at 19 Hz resp. 21.5 Hz dynamic forces of 550 ± 550 N are required for a deformation of ± 3 degrees at the blade tip.
In the dynamic tension tests the inertial mass of the hydraulic piston caused by the rotating clamping of the tensional testing machine reduced these frequencies. Nevertheless, it could be seen, that in case of harmonic excitations the necessary actuator forces to achieve a given angle of deflection are reduced in comparison to static loadings.

For the *third step* an active rotor blade with an integrated piezoelectric stack-actuator was build. The skin of this active model rotor blade was manufactured of fibre composite material using the tension-torsion-coupling effect with one of the above mentioned uncoupling layers between skin and spar. The actuator is supported at the rotor blade spar and generates axial forces at the blade tip. Figure 10 shows the active rotor blade segment with adaptive blade twist.

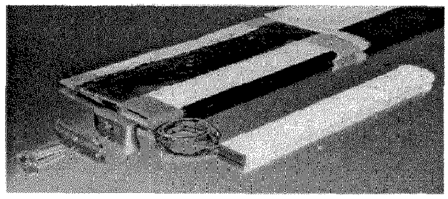

Figure 10: Active rotor blade segment.

In figures 11 the excited eigenmodes (1. Flap at 9 Hz, 2.Flap at 65 Hz and 1. Torsion at 113 Hz) are shown. Near to the torsional resonance frequencies at 113 Hz a deformation of ± 1.5 degrees is possible. For the first flapwise mode at 9 Hz deflections of ±1.2 mm were measured.

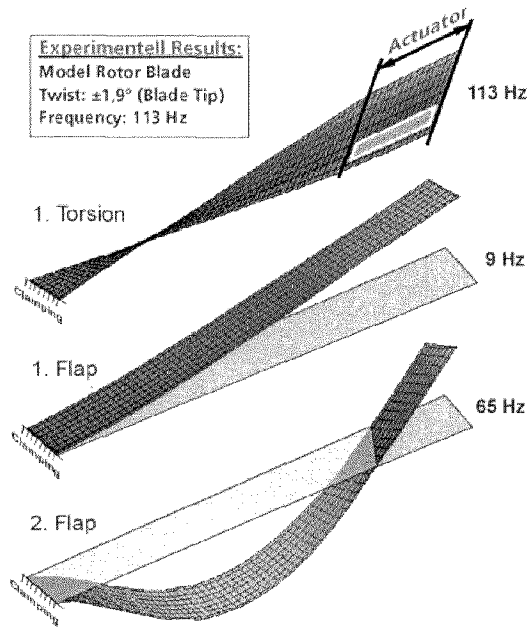

Figure 11: The first three mode shapes (3-dim).

To assess the influence of the aerodynamic, small scale wind tunnel tests were made.
Figure 12 shows for different inflow velocities the static deformations of the adaptive rotor blade segment in the wind tunnel.

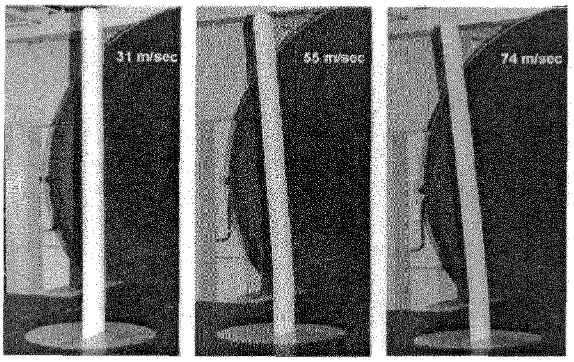

Figure 12: Static Blade Deformations.

The active rotor blade segment excited for different inflow velocities with mono-frequent excitations by 60% of the maximal actuator power. In figure 13 the measurement results are shown. Due to the positive aerodynamic stiffness (aerodynamic neutral axis behind elastic axis) the torsional deformation decreased by the inflow velocity.

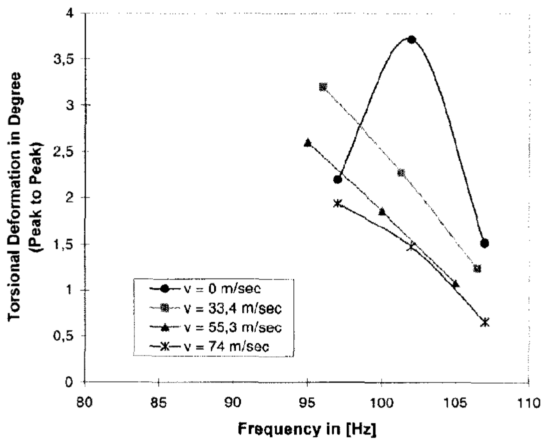

Figure 13: Active Rotor Blade
(60% of the Actuator Power)

It could be demonstrated that actuator systems based on smart materials are certainly able to excite the structure at the required frequencies and with suitable deformations. An adaptive helicopter rotor blade based on the adaptive blade twist concept could be realised. Furthermore these results show that for the rotating case the whole dynamic system has to be optimised for an efficient, dynamic working twist actuator.

With these experimental results it could be shown that:

- an adaptive fibre composite rotor blade based on tension-torsion-coupling can be manufactured.
- the uncoupling layer between skin and spar is suitable to be used for tension-torsion-coupling in rotor blades and
- a piezoelectric stack actuator is suitable to twist the blade. Near to the resonance frequency deformation of ± 1.5 degrees are possible. Therefore the actuated blade section must be specially designed for this.

It could be determined that an adaptive blade twist in the outer part of the rotor is realisable with a comparatively small effort and in its range of application, depending on the form of excitation, it shows to have a very great potential. The realisation of such a control concept, that can go from a static up to a controlled dynamic operation, is dependant on the choice of the actuator. In addition to the demands which the operation puts on this actuator, the installation space, the power specific mass, and the duration of life are further criteria which are decisive for the functionality and efficiency of this drive. Moreover the variety of applications, the small torsional stiffness and the small external forces (inertia force, propeller moment and aerodynamic force) are advantages, which make it attractive to integrate the actuator in the aerodynamically efficient outer part of the rotor. Beside these there are, based on the underlying physics, a lot of other advantages:

- It is possible to influence the aerodynamic forces at the outer part of the rotor. Disturbances induced by the flowfield can be compensated at the source.
- Its has been shown in (14) that for vibration reduction the damping of special blade modes is important. The adaptive blade twist allows active damping for important blade modes.
- Active influence of the blade deflections make it possible to reduce the dynamic stall at the retreating blade.
- Using controllers adaptive aeroelastic systems without instability can be realised.
- There is no increase of the aerodynamic drag. The actuator is completely integrated in the rotor blade and causes controlled changes of the blade twist.

4. Adaptive Camber Variation

The structural concept for an actively controllable camber variation is based upon a 3-cell blade design using tension-torsion-coupling together with piezoelectric stack-actuators to bend the cross-section about the blade axis. A finite-element-model of an adaptive camber rotor blade is used to perform a parameter optimisation to maximise camber variation at the blade tip. Both, geometric as well as material and manufacturing parameters are evaluated.

In contrast to the active twist concepts the adaptive camber concept allows active *shape* control for rotor blades. Furthermore, no flaps or other moving parts are used so that the aerodynamic surface in the deformed state remains smooth without any gaps, edges, or dents.

Since this concept has not yet reached the same level of maturity as the adaptive twist, research efforts currently follow a different approach : prior to a detailed investigation of the aerodynamic effects of an adaptive camber variation first the exact shape of the deformed rotor blade is to be evaluated. The aim is to validate the expected surface quality of the deformed rotor blade and to collect the necessary data about the change of geometry that is required for the subsequent aerodynamic calculations.

4.1 Structural Concept

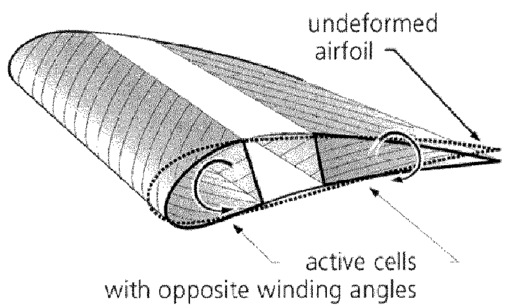

Figure 14: Principle of the Adaptive Camber Variation

The adaptive camber rotor blade has a three-cell cross-section that consists of carbon-glass-fibre composites supported by structural foam.

The desired change of camber is achieved using tension-torsion-coupling in the outer cells that are activated by piezo-electric stack-actuators integrated into the blade tip.

Manufacturing these active cells with helical windings at opposite fibre angles leads to simultaneous upward or downward movements of the blade's edges, as shown in Fig. 14. The resulting continuous change of the rotor blade's camber steadily increases from zero at the root to it's maximum at the tip.

4.2 Finite-Element-Model

The structural concept was investigated using a three-dimensional parametric model designed in a commercial finite-element code ANSYS® 5.3 (see Fig. 15). Aerodynamic as well as structural loads were not considered in the design of this model, since only the deformed airfoil's surface quality was of interest here. For the same reason, neither spars nor ribs were represented in the model rotor blade.

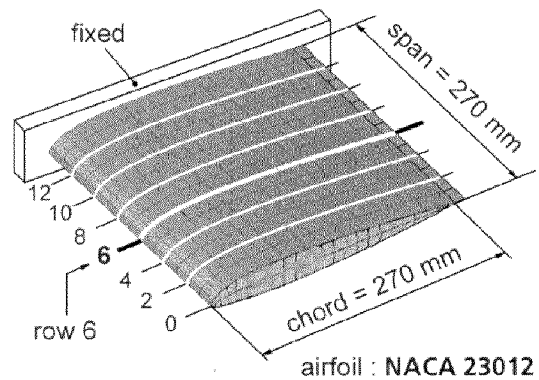

Figure 15: Finite Element Discretisation

Three different materials were used in the design of the ummerical model: Carbon-fibre-composite, glass-fibre-composite and structural foam.

The carbon-fibre-composite was used in the helical winding layers of both active cells to realise the desired tension-torsion-coupling. This composite consists of HM carbon fibre and epoxy resin with 60% fibre volume fraction.

The outer skin of the model consists of glass-fibre-composite made from glass fabric (100 g/m^2) oriented at 45°. Resin material and fibre volume fraction were assumed to be the same as in the carbon-fibre composite.

Foam cores were used in each of the three cells to support the fibre layers and to guarantee the desired airfoil's shape.

The manufacturing process of a rotor blade equipped with active camber variation was supposed to begin with the active cells. First the helical carbon-fibre unidirectional (UD) layers were attached to the foam cores. Next the two outer cells were connected to the middle cell's foam core. Last the glass-fibre layers were attached as the outer skin in order to finish the rotor blade.

This process is not suitable for the design of a real rotor blade including structural and aerodynamic loads. Yet it was feasible for the proof-of-principle demonstration structure, that was required later to experimentally validate the expected deformation properties of this concept. The proposed manufacturing process determined the composite lay-up for the model, as it is shown in Fig. 16 for the model's cross-section.

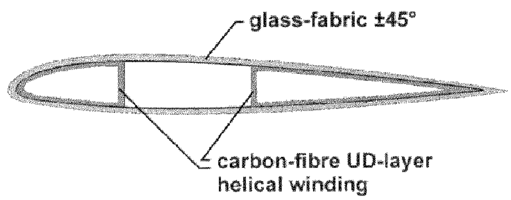

Figure 16: Composite Lay-up

Geometric as well as material parameters were considered in the evaluation of the adaptive camber concept.

Three groups of parameters were evaluated:

- the positions of the inner cell walls,
- the fibre angles of the carbon-layers, and
- the thickness of carbon- and glass-layers.

The inner cell walls' positions were given in percent chord, ranging from 15 % to 70 % for the front wall and from 35 % to 85 % for the rear wall. These parameter boundaries were arbitrarily chosen in order to allow for a wide range of possible cell wall position combinations. Furthermore, the rear wall was locally restricted, so that it was always positioned behind the front wall. This precaution was necessary for the subsequent automatic parameter optimisation. The increment was set to 5% c for both walls to keep the number of wall position combinations small.

The fibre orientation of the carbon-fibre layers ranged from 0° to 45° in the leading edge cell and from -45° to 0° in the trailing edge cell. An angular increment of 5° was chosen for both cells due to restrictions in manufacturing precision. The active cells' orientation angles were independend of each other.

The thickness of the carbon- and glass-fibre layers varied from 0.2 to 5 mm for each layer with a 0.2 mm increment according to manufacturing accuracy.

These seven parameters (2 cell wall positions, 2 fibre angles, 3 thicknesses) were investigated in the following calculations to gather information over the parameters' influence on the maximum camber variation.

4.3 Evaluation

In each of the subsequent calculations a different set of parameter values was evaluated concerning the maximum change of camber, the rearward position of this maximum, and the angle of attack at element row 6 (as illustrated in Fig. 15). These data were extracted from nodal positions and displacements within each program run and stored for later data processing.

The change of camber was calculated from the difference between the mean lines of the undeformed and the deformed rotor blade model. Therefore, the mean lines had to be extracted from the positions of FE nodes in each program run.

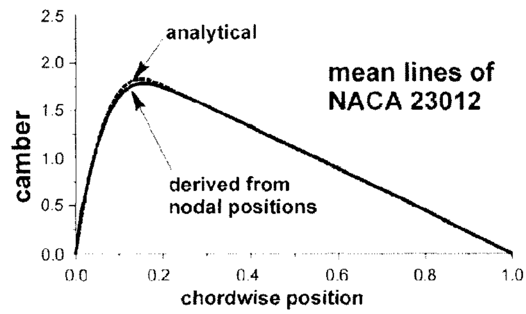

Figure 17: Comparison of Mean Lines

To prove the feasibility of this approach, the mean line of the NACA 23012 was derived from the nodal positions in the FE-model and compared to the mean line calculated from the analytical formula. The maximum difference was less than 0.1 % of the analytical mean line. This accuracy was sufficient for the subsequent parameter investigations.

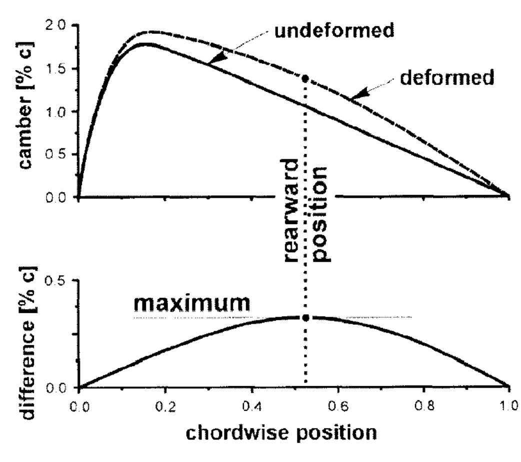

Figure 18: Change of Camber

The difference between undeformed and deformed airfoil camber gave the change of camber.

For the final evaluation of this change of camber only its maximum and the rearward position of this maximum were used, see Fig. 18.

Since both leading edge and trailing edge of the airfoil change their position when the camber variation is activated, an influence on the angle of attack was expected. For this reason, the angle of attack was derived from the displacements of the leading and trailing edge nodes prior to the evaluation of the change of camber. Afterwards, the coordinate system was rotated to compensate for the calculated blade twist before the change of camber was evaluated. In this way, the two degrees of freedom camber variation and blade twist could be investigated separately.

In general, the deformed airfoil's shape would be between two extremes. Case 1 has a rearward position of maximum change of camber between 45 %c and 50 %c and a positive angle of attack; case 2 has a rearward position of maximum change of camber beyond 65 %c and a negative angle of attack (Fig. 19).

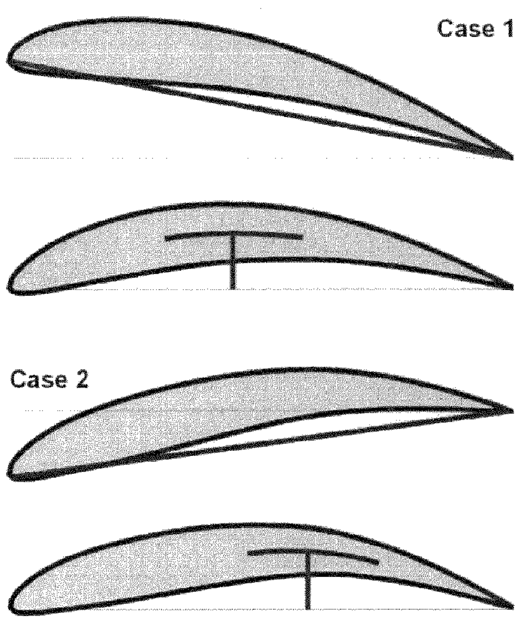

Figure 19: Two General Deformation Modes

All three parameter groups proved to have similarly great influence on the camber variation. Therefore, it was necessary to identify the combination of parameters, that yielded the largest change of camber.

4.4 Optimisation

Using the automatic optimisation capabilities of the FE-program, a parameter optimisation was performed. The thickness of the glass-fabric layer was set to 0.2 mm, all other parameters were free for variation within the given limits.

For the optimisation the resulting angles of attack were restricted to positive values, the rearward position of the maximum change of camber was constrained not to exceed 60% chord.

Under these conditions the maximum change of camber reached 0.547% chord. This was obtained from the following parameter combination :

front cell wall at 35% chord

rear cell wall at 55% chord

front carbon fibre orientation −20°

rear carbon fibre orientation 20°

carbon fibre thickness 2.0 mm

The maximum's rearward position was 52,5% chord, the angle of attack in this case was less than 0.01°.

To further increase the change of camber, it would be necessary to allow rearward positions beyond 60% chord and to accept negative angles of attack. This decision has to be taken carefully with respect to the aerodynamic effects of such an airfoil variation.

4.5 Aerodynamic Effects of Camber Variation

In order to assess the effects of the camber variation on an airfoil's aerodynamic performance, the stationary characteristics of the deformed airfoil were calculated in 2D. Therefore, the deformed airfoil shape calculated in the FE environment was transfered to a CFD viroment to derive the desired polares.

Fig. 20 illustrates the changes in the lift coefficients c_L as a function of the angle of attack for the case 1 deformation of the NACA 23012.

Both, the effect of the camber plus the angle of attack and the effect of the camber only were investigated. The trends given in Fig. 20 were derived by scaling the deformation from the FE-calculations with a factor of 5, in order to illustrate the effect of the deformation quality.

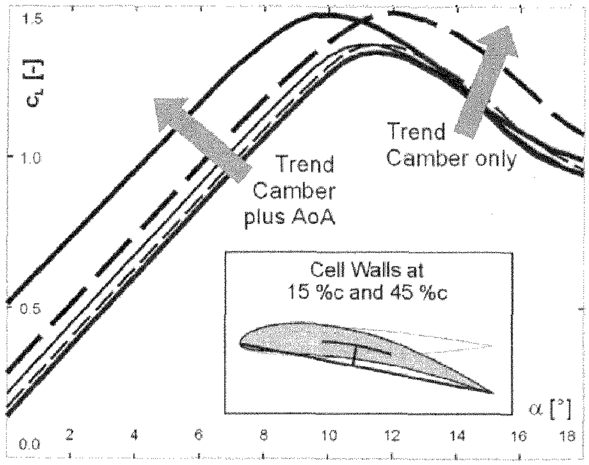

Figure 20: Aerodynamic Effects of Camber Variation

The camber variation concept proved to have the expected surface qualities in the deformed state. Steps to be taken include the consideration of thin airfoils (9% and less) to increase the maximum change of camber. Next a demonstration structure is to be designed and manufactured. The goal is to experimentally validate the deformation qualities and to investigate the dynamic properties and deformation quantities. As soon as the aerodynamic requirements are investigated another demonstration structure can be designed and manufactured taking into account the static and dynamic structural and aerodynamic loads.

5. Conclusions and Outlook

It could be demonstrated that actuator systems based on smart materials are certainly able to excite rotor blades at the required frequencies, so that a smart helicopter blade can be realised. At a lower level of maturity, a structural concept to actively change a rotor blade's aerodynamic shape in operation showed to have great potential to increase rotorcraft efficiency.

The solution of technical problems by means of adaptive structural technology must continue to be considered as a new field of research. Furthermore, the adaptive structural technology for helicopter applications is highly interdisciplinary and requires a considerable amount of research work. The comprehension of helicopter dynamics and aeroelastic interaction with the integrated adaptive structural technology is very important to reach an optimised helicopter design. A detailed evaluation of the effectiveness of this adaptive control approach can only be made on the basis of the understanding of the underlying physics. Therefore this work will be accompanied

- by investigations of alternative concepts of integrated actuators based on piezoceramic stacks, plates, films and fibres.
- by additional experimental investigations with aerodynamic loads of wind tunnel tests in nonrotating and rotating cases and
- by investigation of full-scale applications.

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