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ADAPTIVE BLADE TWIST
CALCULATIONS AND EXPERIMENTAL RESULTS

by

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ADAPTIVE BLADE TWIST - CALCULATIONS AND EXPERIMENTAL RESULTS

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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. This paper presents recent investigations on a very promising specific concept described as *Adaptive Blade Twist* (ABT). This 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. Since the interaction of non-stationary helicopter aerodynamics and elasto-mechanical 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 the structural concept. With respect to these considerations, the ABT concept will be presented.
This concept bases on the actively controlled tension-torsion-coupling of the structure. For this, an actuator is integrated within a helicopter blade that is made of anisotropic material based on fiber composites. 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 paper starts at giving a review on conventional concepts and potential adaptive solutions for shape control [2],[3],[9],[13]-[15].
Hereafter, some calculations of the adaptive twist control concept are presented. These are based on a representive model in which the active part of the rotor blade is simplified with a thin-walled rectangular beam, that is structurally equivalent to a model rotor blade of the Bo105 with a scaling factor 2,54. The calculations are performed using an expanded Wlassow Theory. 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 this preconditions. This has been demonstrated and verified in experiments [7] which will not be discussed in this paper.

For experimental investigations on the ABT concept the skin of the outer part of the model rotor blade was manufactured of fibre composite material using the above mentioned tension-torsion-coupling effect with an additional uncoupling layer between skin and spar. The experimental results have shown that near to the resonance frequency dynamic forces of 550 ± 550 N are required for a deformation of ± 3 degrees at the blade tip.

1. LIST OF SYMBOLS

A(r,t)	: lifting force [N]
B	: warping force [Nm²]
F	: axial force [N]
H	: torsional moment [Nm]
I_θ	: inertia mass (torsion)
I_u	: inertia mass (warping)
L	: elongation [m]
l	: lenght of the beam [m]
m	: mass [kg/m]
$M_R(r,t)$	: rudder moment [Nm]
M_s	: bending moment [Nm]
m_s	: bending moment per unit length [N]
N_z	: axial force [N]
n_z	: axial force per unit length [N/mm]
P	: longitudinal force [N]
t_{zs}	: shear force per unit length [N/mm]
U	: warping deflection
v(r,t)	: inflow velocity [m/sec]
d_1,t_1,d_2,t_2	: dimensions (rectangular cross section)
D_{ij}	: extensional stiffnesses
B_{ij}	: bending stiffnesses
K_{ij}	: matrix coefficients
n,s,z	: coordinate system axes (skin elements)
x,y,z	: coordinate system axes (beam)
α	: fiber angle [deg]
ε_z	: longitudinal strain [-]
γ_{zs}	: shearing strain [-]
$\varphi_i(s)$	: shape function (longitudinal)
κ_s	: middle surface curvature [-]
θ	: torsional angle [deg]

ω : frequency [1/sec]

Ω : revolution per minute [rpm]

2. 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.

In general, helicopter vibrations and noise result 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 forward moving blade. All these vibrations are of a highly dynamic nature.

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 dynamic 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.

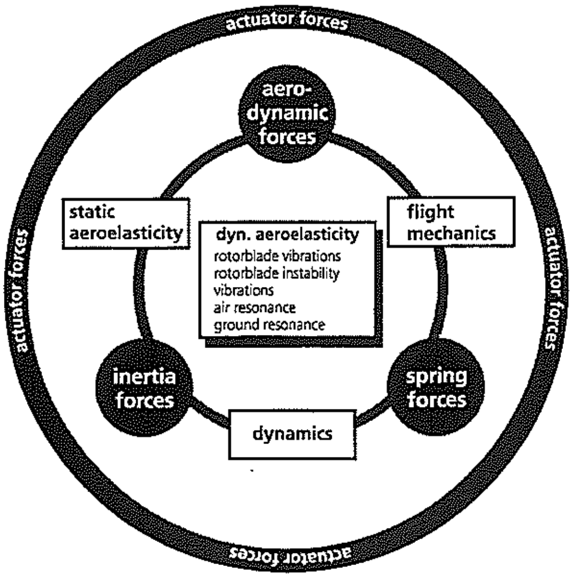

Figure 1: Adaptive aerolastic system

The angle of attack and the inflow velocity in all occurrences of aerodynamic effects are very important and very sensitive to small variations. 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.

3. 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 actuation's at the blade root. This can be done by the use of control rods or, alternatively, by designing an adaptive blade root.

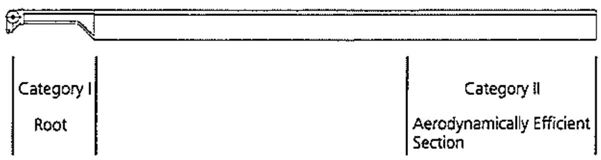

Figure 2: Locations for the use of adaptive material systems

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 in turn act on the blade motion.

One example which falls within category II is the *adaptive camber variation*, which investigates active deformations of the cross-section on rotor dynamics. The principle of this actuator concept is presently being developed at the DLR [10]-[12].

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 third concept is the *adaptive twist control* shown in figure 3. Investigations on this concept will be described in detail below.

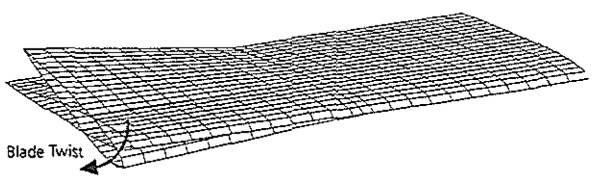

Figure 3: Adaptive twist control

4. 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 servoflap [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]

Torsion caused by a servoflap

According to this actuator concept, the flap deflection should produce aerodynamic rudder moments leading to a torsional deflection of the blade. The efficiency of the flap 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*.

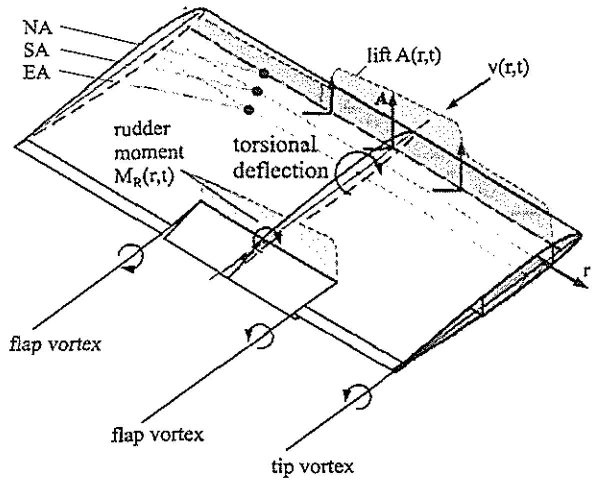

Figure 4: Different approaches by using flaps

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

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.

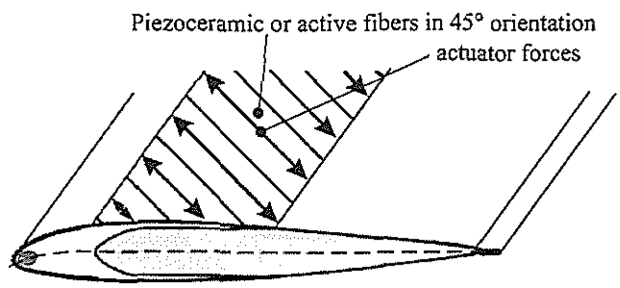

Figure 5: Torsion induced by tension forces

The advantage of this simple, in the flux of work acting concept, is the good control characteristic. One disadvantage of this concept is the insufficient damage tolerance behaviour.

Torsion due to torsion-warping-coupling

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

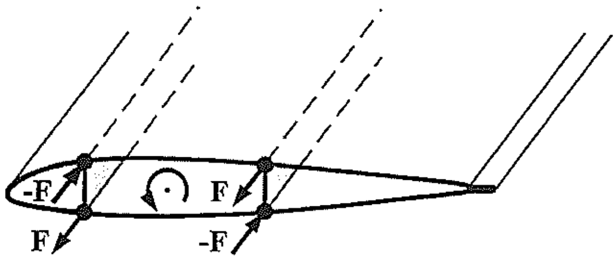

Figure 6: Torsion induced by warping forces

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 by implementing this concept into a rotor blade.

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 must be distinguished 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.

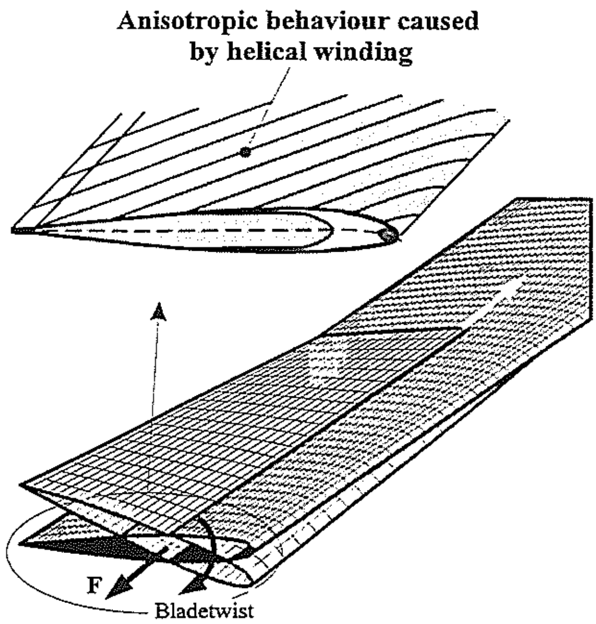

Figure 7: Adaptive blade twist

For practical realisation, cylindrical actuators like piezoelectric elongators (piezo-stacks) can also be employed. 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]

5. Actuator Requirements

There are a lot of different types of actuators[1]. For the right actuator selection the necessary power depending on the static or dynamic use of the actuator, the installation space, the power specific mass and the duration of life are important criteria to determine the functionality and efficiency of a drive.
The goal of this investigation is to calculate the deformation behaviour and the preliminary dimension of the actuator. For this structural dynamic investigation of the rotor blade with active blade twist using anisotropic material behaviour in the outer part of the rotor, a description of the whole rotating blade is necessary. The structural dynamic model to calculate the active rotor blade is shown in figure 8.

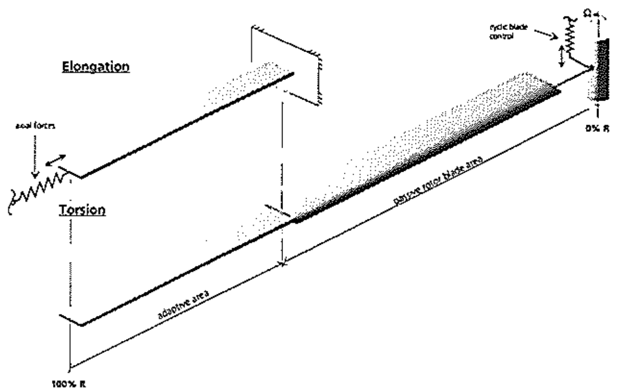

Figure 8: Dynamic structural model for a rotor blade

To carry out computations the active part of the rotor blade is represented by a tension-torsion-coupled, thin-walled rectangular beam. This beam is similar to a model rotor blade of the Bo105 (scaling factor 2.54) concerning inertial moment- and stiffness distribution. The geometry and construction of this box-beam are shown in figure 9.
The calculation of this beam is based on an extended Wlassow theory. In general, the theory of thin-walled elastic beams has to satisfy three conditions:

1. the bending moment per unit length of a section perpendicular to z-axes $m_z=0$
2. the twisting moment per unit length of a section $m_{zs}=0$
3. the circumferential stress of the beam $\sigma_s=0$

which reduce the shell-theory to a theory of thin-walled shells, e.g. beams [16], [17], [1].

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[1] hydraulic, pneumatic, electric, mechanic, piezoelectric, electrostrictive, magnetostrictive, ...

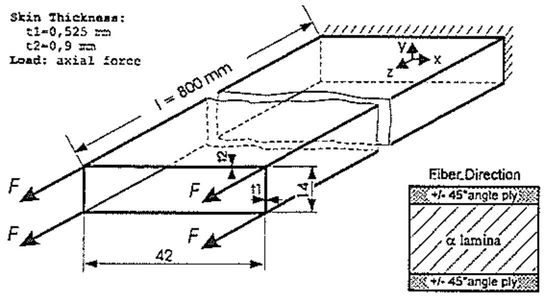
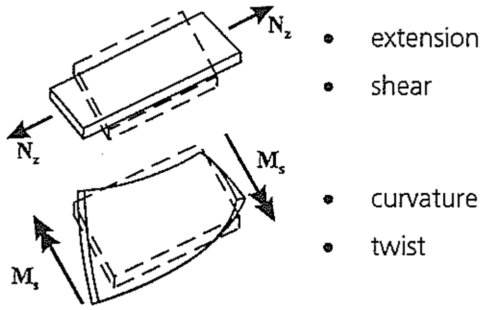


Figure 9: Geometrical configuration of the boxbeam

The stress-strain relationship referring to the cross-section area of a laminate with linear anisotropic material behaviour, a symmetric lay-up, and unbalanced orientations of the fibre directions, is represented by

$$\begin{pmatrix} n_z \\ t_{zs} \\ m_s \end{pmatrix} = \left[\begin{array}{cc|c} \overline{D}_{11} & \overline{D}_{13} & 0 \\ \overline{D}_{13} & \overline{D}_{33} & 0 \\ \hline 0 & 0 & \overline{B}_{22} \end{array}\right] \cdot \begin{pmatrix} \varepsilon_z \\ \gamma_{zs} \\ \kappa_s \end{pmatrix}$$

which satisfies the Kirchhoff's law and the conditions for the expanded Wlassow-Model to describe thin-walled elastic beams. In figure 10, the deformation behaviour is shown.



- extension
- shear
- curvature
- twist

Figure 10: Deformation behaviour

In the case of dynamic axial forces, the influence of forces due to inertia can be implemented into the differential equations by external loads. The differential equation for the dynamic system is given by

$$\begin{pmatrix} L \\ U \\ \theta \\ P \\ B \\ H \end{pmatrix}' = \left[\begin{array}{ccc|ccc} 0 & K_{LU} & 0 & K_{LP} & 0 & K_{LH} \\ 0 & 0 & 0 & 0 & K_{UB} & 0 \\ 0 & K_{\theta U} & 0 & K_{LH} & 0 & K_{\theta H} \\ \hline 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & K_{BU} & 0 & K_{LU} & 0 & K_{\theta U} \\ 0 & 0 & 0 & 0 & 0 & 0 \end{array}\right] \cdot \begin{pmatrix} L \\ U \\ \theta \\ P \\ B \\ H \end{pmatrix} + \left[\begin{array}{ccc|ccc} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ \hline m & 0 & 0 & 0 & 0 & 0 \\ 0 & -I_U & 0 & 0 & 0 & 0 \\ 0 & 0 & I_\theta & 0 & 0 & 0 \end{array}\right] \cdot \begin{pmatrix} \ddot{L} \\ \ddot{U} \\ \ddot{\theta} \\ \ddot{P} \\ \ddot{B} \\ \ddot{H} \end{pmatrix}$$

The rotor blade modelled by a thin-walled elastic beam and calculated by this expanded Wlassow theory is a simple, flexible design tool, which can be used for preliminary optimisations. The applied dynamic system has been investigated for two load-cases:

I. *Excitation due to axial elongations at the blade tip.* - The elongations at the blade tip depends on the axial deformations of the actuator. Stiffness and inertial forces effect the required actuator forces.

II. *Excitation due to axial forces at the blade tip.*

In this numerical investigation the structural response to static and dynamic loads with excitation frequencies of 1Ω=17.5Hz, 2Ω=35Hz, 3Ω=52.5Hz, and 5Ω=87.5Hz were calculated. The results in form of the first three torsional eigenmodes and the deformation and force distribution are presented in figures 11 to 15.

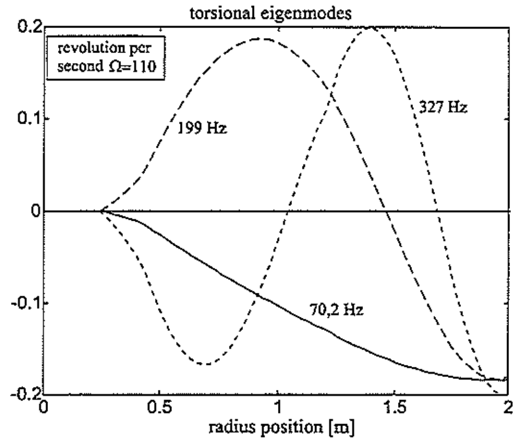


Figure 11: The first 3 mode shapes of torsion.

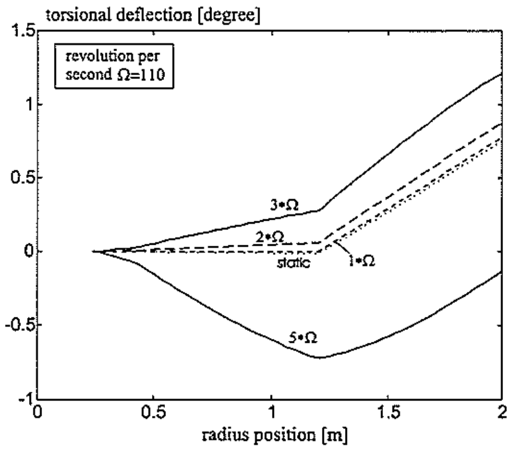


Figure 12: Distribution of the torsional deformation.

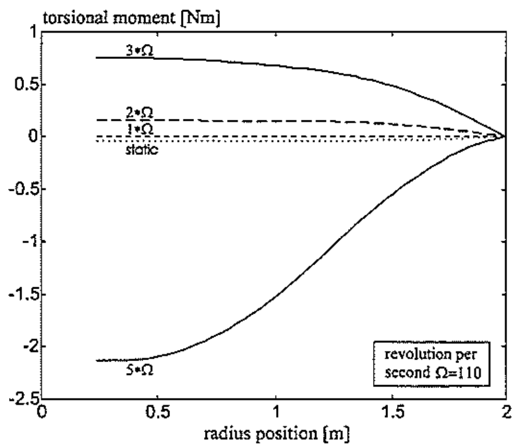


Figure 13: Distribution of the torsional moment.

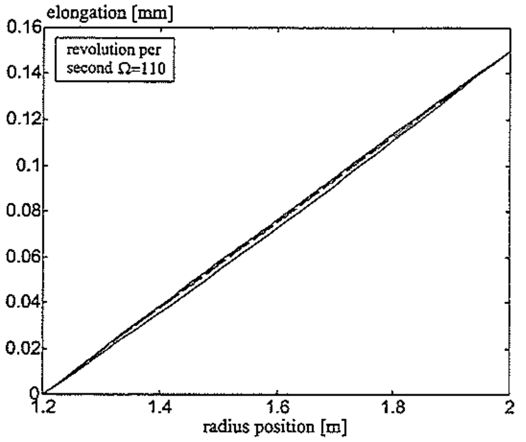


Figure 14: Distribution of the elongation (active part).

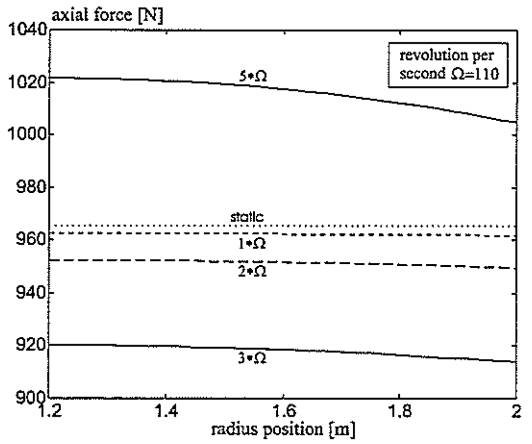


Figure 15: Distribution of the axial force (active part).

The torsional deflection of the passive blade area due to static loads (figure 11) is caused by the propeller moment. In the outer part of the rotor blade the actively generated torsional deflection is reduced by the propeller moment. The same result is shown in figure 12. In the static case the distribution of the torsional moment is only caused by the propeller moment.

By the dynamic load-cases the passive blade is mainly excited by the inertia moments of the active blade. The counteracting propeller moments influence decreases with increasing excitation frequency. The propeller moments are equal to the inertia moments for a excitation with 1Ω. At excitation frequencies above 1Ω the inertia moments are always higher than the propeller moment. [2]

Up to the resonance frequency (here 70.2 Hz) the direction of the torsional deflection at the active and passive rotor part are equal. Above of the resonance the torsional deflections are not in phase.

The necessary actuator forces are shown in figure 15. They are equal to the axial forces at the blade tip.

[2] For a excitation with 1Ω the propeller moments $\Omega^2 I_\theta \theta$ are equal to the inertia moments $-\omega^2 I_\theta \theta$. The twist is only caused by the tension-torsion-coupling.

Due to the tensions-torsion-coupling the inertia moments influence the axial forces so that the excitation frequency causes changes in the necessary actuator force. The different boundary conditions due to the load-cases causes a displacement of the torsional eigenfrequencies. In *Case I* for example, the axial force at the blade tip is predetermined and the elongation *free* (not fixed). Whereas in *Case II* the axial elongation is predetermined. The tension-torsion-coupling is the reason for this interaction. The following table shows the first three eigenfrequencies depending on the load-cases:

Excitation	1. Mode	2. Mode	3. Mode
Case I	70.2 Hz	199 Hz	327 Hz
Case II	68.9 Hz	187.4 Hz	320 Hz

Besides the above presented deformation behaviour of the adaptive rotor blade, the necessary actuator power depends on different excitation frequencies which were qualitatively determined. A quantitative comparison of these results is not suitable because there is no damping and no aerodynamic involved in the calculation.

Table 1 shows the results for the static and the dynamic loading with excitation frequencies of 1Ω, 2Ω, 3Ω and 5Ω. The torsional deflection is described by two values. Furthermore the axial elongation and force at the blade tip and the necessary actuator work and power (without dissipation) are given.

Freq.	Case	θ [degree]	L [mm]	F [N]	F*L [Joule]	Power [Watt]
static	I	2 (−0.04)	0.398	2559.9	1.02	—
	II	2 (−0.04)	0.398	2559.9	1.02	—
1 Ω = 17.5Hz	I	2 (0)	0.385	2468.7	0.95	16.63
	II	2 (0)	0.385	2468.7	0.95	16.63
2 Ω = 35Hz	I	2 (0.14)	0.342	2165.4	0.74	25.92
	II	2 (0.14)	0.342	2165.4	0.74	25.92
3 Ω = 52.5Hz	I	2 (0.46)	0.247	1503.3	0.37	19.47
	II	2 (0.46)	0.234	1503.3	0.35	18.44
5 Ω = 87.5Hz	I	−0.2 (1.1)	0.224	1497.4	0.33	29.29
	II	−0.2 (1.1)	0.224	1497.4	0.334	29.29

Table 1: Actuator requirement (without dissipation).

The two characteristic values describing the torsional deflection are the deflections at the blade tip and at the transition from the active to passive blade. These second values characterise the excitation of the passive blade section by the active blade section.

There are no results for an excitation with 4Ω since this excitation frequency is near the resonance and in this investigation is no damping is considered.

It could be shown:

1. that the torsional mode shape depends on the excitation frequency.

2. that the differences in the kind of excitation (axial elongation or axial force) cause differences in the boundary conditions and thus a shift of the torsional eigenfrequency.
3. that the axial elongation at the blade tip necessary to achieve a desired twist angle is independent of the load case.
4. that for a static torsional deformation of 2° at the blade tip, an elongation of 0.4 mm is needed and (length of the blade: 800mm ⇒ 0.5‰ strain)
5. that due to the excitation of the passive blade area, for dynamic excitations above from 1Ω the torsional deflection blade tip increases.

Based on these results the actuator must be capable of exerting the axial force that causes the desired torsion against any internal and external loads. Therefore, among the stiffness- and inertia forces the centrifugal- and the aerodynamical forces are decisive for a final dimension of the adaptive rotor blade.

6. 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] which will not be discussed in this paper.

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 the points of interest of these experimental investigation. 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 16.

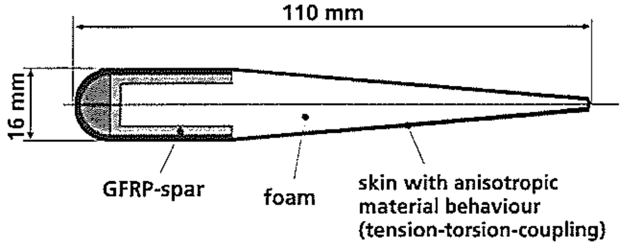


Figure 16: Simplified cross-section.

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 17a and 17b.

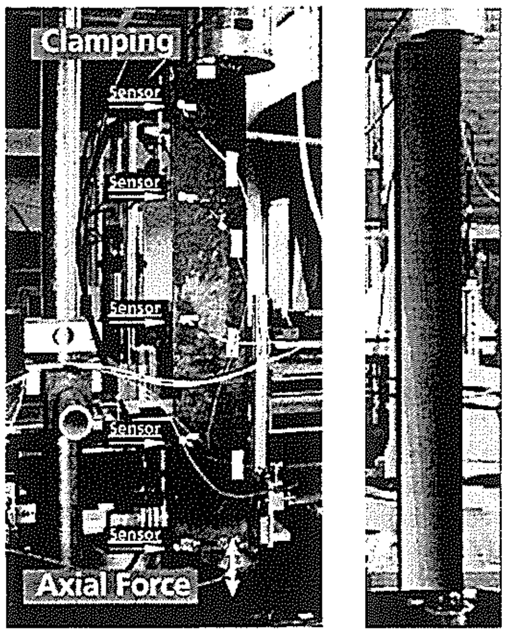


Figure 17a: Experimental configuration.
(Blade Segment w. Tension-Torsion-Coupling).

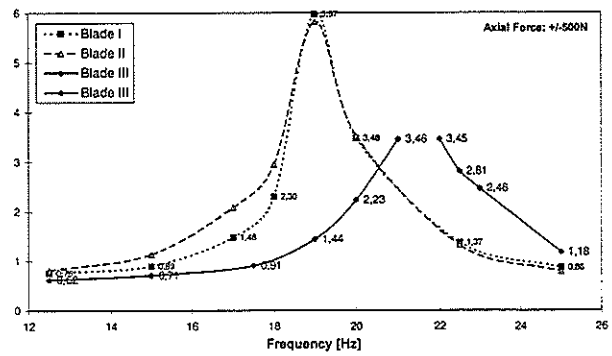


Figure 17b: Results from the dyn. tension test.

The right picture of figure 17a shows the measured deflections out of plane of *Blade I* at 19 Hz. It could be shown that for all uncoupled layers linear twist distributions are excited.

Figure 17b 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 (figure 18) 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.

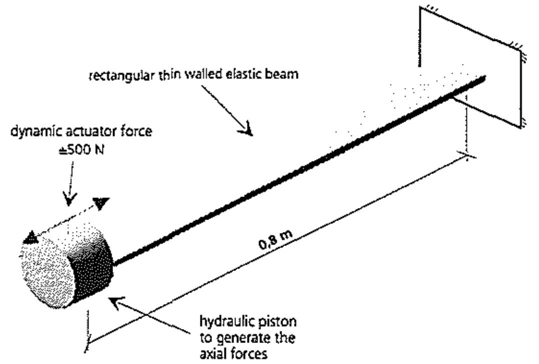


Figure 18: Configuration from the dyn. tension test.

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 19 shows the active rotor blade segment with adaptive blade twist.

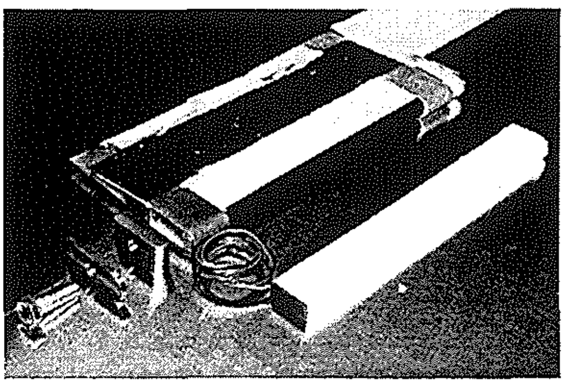


Figure 19: Active rotor blade segment.

In figures 20 and 21 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.

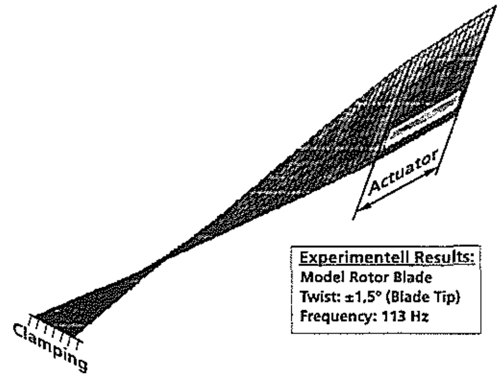


Figure 20: Mode shape of the 1 torsion (3-dim).

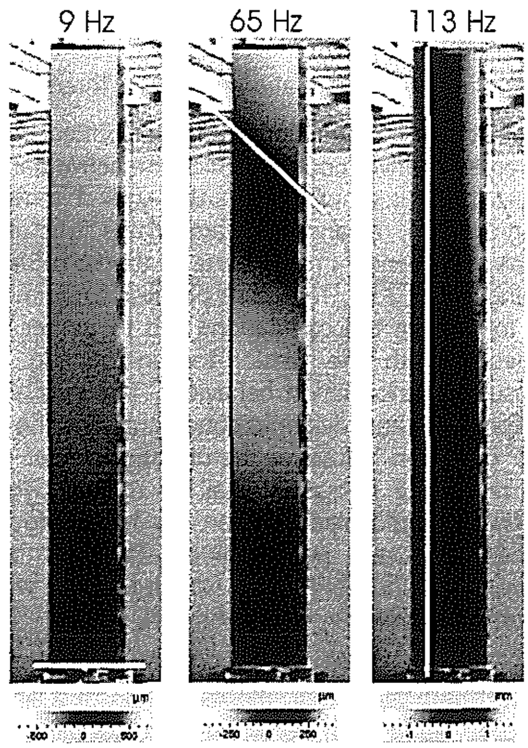


Figure 21: The first three mode shapes (2-dim).

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.

7. Conclusions and Outlook

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 determine the functionality and efficiency of this drive. Moreover the variety of applications, the small torsional stiffness and the small external forces strengths (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.
- The using of controllers make adaptive aeroelastic systems with no instability possible.
- 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.

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 blades can be realised. Nevertheless, 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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