

Modelling of a Rotor Blade with Piezoelectric MFC Actuators [†]

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Abstract

A numerical study was conducted to investigate the effect of embedded piezoelectric actuators integrated into the skin of a model-scale BO105 rotor blade on its torsional behaviour. The analysis was performed for blades with different combinations of spar and skin materials, including UD GFRP and UD CFRP composites. Four finite element models of the helicopter blade were developed in ANSYS 16.0. The piezoelectric response of the MFC (Smart Material Corp., Sarasota, FL, USA) actuators was simulated using a thermal analogy approach. The effects of actuator placement, as well as the selection of spar and airfoil skin materials, on the torsion angle and structural characteristics of the blade were analysed. The largest torsional angle was obtained for rotor blade configurations equipped with MFC actuators and manufactured entirely from UD GFRP composites. The spar material did not affect the torsional angle.

Keywords: ANSYS; piezoelectric; helicopter; blade; twist control

1. Introduction

A major issue with helicopters in flight is the significant vibration and increased noise levels caused by aerodynamic loads acting on the main rotor blades. Creating a helicopter rotor blade control system to reduce noise and vibration is one of the priority goals for engineers. At present, several methods exist for actively controlling helicopter main rotor blades during flight. One approach used to suppress vibrations is Higher Harmonic Control (HHC). Through the swashplate, high-frequency harmonic inputs are applied to the blades to compensate for vibrations and aerodynamic loads. The disadvantage of this method is the use of the helicopter's main control system to transmit higher harmonics to the rotor blades. If the main control system fails, a pilot partially loses control of the helicopter. Another way to reduce vibrations is the Individual Blade Control (IBC) method, in which each rotor blade is controlled independently. The main disadvantage is a decrease in flight safety due to interference with the helicopter's primary control system and the application of additional high-power actuators [1].

With the advent of a new type of piezoelectric actuators, new methods of IBC have begun to be developed, allowing for the optimisation of aerodynamic performance, reduction in vibrations, and improvement of rotor efficiency in real time. Active Trailing Edge is based on the deformation of the rear part of the rotor blade. Bending deformation of the trailing edge leads to a change in the geometry that modifies the aerodynamic load distribution along the blade span [2,3].

Active Twist technology is based on the integration of piezoelectric actuators directly into the rotor blade skin. These actuators are embedded in the upper and lower skins using



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fibres oriented at an angle of $\pm 45^\circ$. When an electric field is applied, the piezoelectric elements deform, causing a torsional displacement of the blade. This controlled twisting allows the aerodynamic characteristics of the blade to be adjusted dynamically [4–8].

Research into the use of piezoelectric materials for vibration reduction began in the early 1990s. At first, numerical studies focused on simplified models of helicopter blades. The experimental tests were limited due to the rigid and inflexible structure of piezoceramics [9,10]. The development of piezoelectric fibres marked a turning point, leading to a new generation of piezoelectric actuators, which were more flexible and could be mounted on curved surfaces [11,12].

This work presents a preliminary analysis of the BO105 model-scale rotor blade with MFC actuators. Four numerical models of the helicopter blade were considered, depending on the type of material in the spar and the skin. The influence of skin and spar material selection on the torsion angle and blade characteristics is considered as a function of the piezoelectric MFC actuators' placement. Methods for determining the cross-section stiffness characteristics and model parameters are being developed. Further results of this parametric research will be used for modelling and research of the BO105 helicopter blade in full-scale.

2. Methods and Materials

In this study, the scale model of the BO105 composite rotor blade was investigated. The cross-section of the BO105 rotor blade (DLR, Braunschweig, Germany) is shown in Figure 1. The rotor blade has a NACA 23012 airfoil and is configured without geometric twist. The nose contains a lead balance weight and erosion protection. The blade skin and spar are manufactured from unidirectional glass fibre reinforced polymer (UD GFRP).

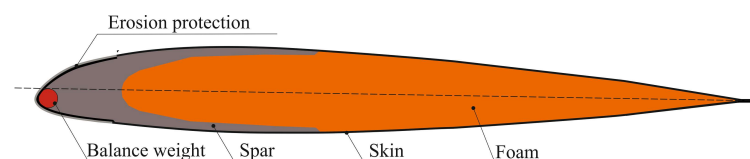


Figure 1. The cross-section of the BO105 rotor blade.

The internal cross-sectional dimensions of the blade model in numerical research are presented in Figure 2. The blade in numerical modelling has a span of 1560 mm. The chord-wise length is 121 mm. The skin's thickness is 0.5 mm and consists of four layers with $[+45^\circ / -45^\circ]$ stacking sequence.

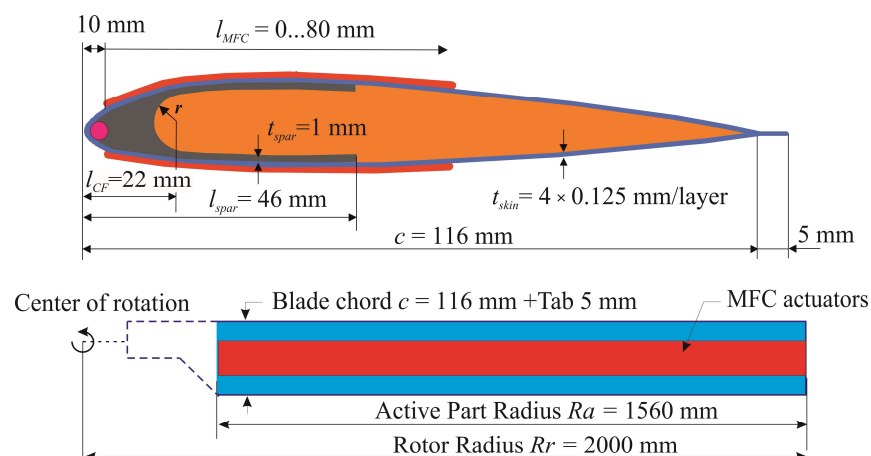


Figure 2. Geometric dimensions of the model-scale blade.

The cross-section of the spar is simplified for the subsequent solution of the parametric problem. The GFRP fibres in the spar are oriented along the span. MFC actuators are modelled on the upper and lower surfaces of the rotor blade with a fibre orientation of $+45^\circ$ and -45° .

Inside the MFC, actuators are situated in piezoceramic fibres with a rectangular cross-section [13]. The fibres are arranged in an epoxy matrix, spaced slightly apart from each other. Polyamide films with embedded electrodes are positioned above and below the epoxy matrix. The thickness of this assembly is 0.3 mm. The orientation of the piezoceramic fibres coincides with the orientation of the outer fibreglass layers on the surface of the helicopter blade. This arrangement increases the blade's torsional capacity. When an electric field is applied, the piezoelectric effect is activated, and the fibres change their length. The change in fibre length causes shear deformation on the blade surface, generating torque along the blade span. The piezo actuators are arranged on the surface of the blade as a rectangular active layer along the entire length of the blade.

The mechanical properties of the materials used in the composite blade for the numerical analysis are summarised in Table 1.

Table 1. Mechanical properties of the materials used in the composite blade: Young's modulus E_i , Shear modulus G_{ij} , Poisson's ratio ν_{ij} , Density ρ , Piezoelectric constant, d_{ij} .

Symbol	UD GFRP *	UD CFRP **	Foam	Lead	MFC
E_1 [GPa]	45.166	139.366	0.035	13.790	30.000
$E_2 = E_3$ [GPa]	11.981	8.741	0.035	13.790	15.500
$G_{12} = G_{13}$ [GPa]	4.583	4.858	0.014	2.000	5.700
G_{23} [GPa]	1.289	1.289	0.014	2.000	10.700
$\nu_{12} = \nu_{13}$	0.238	0.268	0.25	0.44	0.31
ν_{23}	0.325	0.325	0.25	0.44	0.16
ρ [kg/m ³]	2008	1552	52	11,300	4700
$d_{31} = d_{32}$ [m/V]	-	-			-1.98×10^{-10}
d_{33} [m/V]	-	-			4.18×10^{-10}

* UD GFRP is unidirectional glass fibre-reinforced polymer, ** UD CFRP is unidirectional carbon fibre-reinforced polymer.

The finite element (FE) rotor blade model is created in ANSYS 16 software using SHELL 281 elements (multilayer skin) and SOLID 186 elements (balance weight, spar, and foam core). The MFC actuators are modelled using SHELL 281 elements as a separate layer in the blade skin (Figure 3).

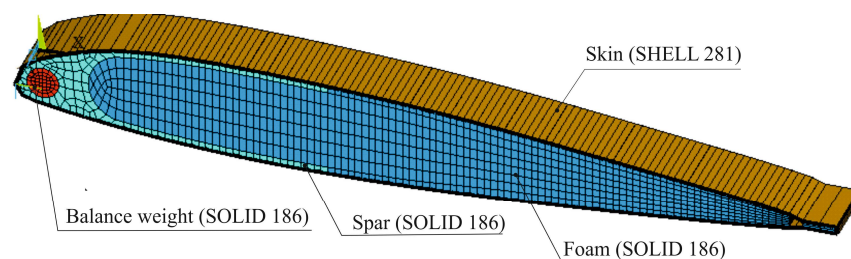


Figure 3. Dimensions of the cross-section.

Since the SHELL 281 element possesses both translational and rotational degrees of freedom at its nodes, whereas the SOLID 186 element includes only translational degrees of freedom, a preliminary numerical investigation was carried out to assess the compatibility of these finite-element types. The results demonstrated that with an appropriately defined coupling scheme, stable and consistent transfer of displacements and strains across the

interface is ensured. To simulate real-world attachment conditions, a rigid attachment (clamped boundary condition) was applied to the root section of the blade.

A thermal analogy was used to simulate the piezoelectric effect in a finite element model of a composite rotor blade with MFC-actuator piezoelectric layers (Figure 4). The analogy is based on the use of thermal expansion coefficients in piezoelectric actuators instead of piezoelectric coefficients. The thermal expansion coefficients are calculated as [14,15]:

$$\alpha_{ij} = \frac{d_{ij}}{\Delta} \quad (1)$$

where d_{ij} represents the piezoelectric coefficient and Δ denotes the distance between electrodes ($\Delta = 0.5$ mm). The electrical voltage on the actuators was 1000 V.

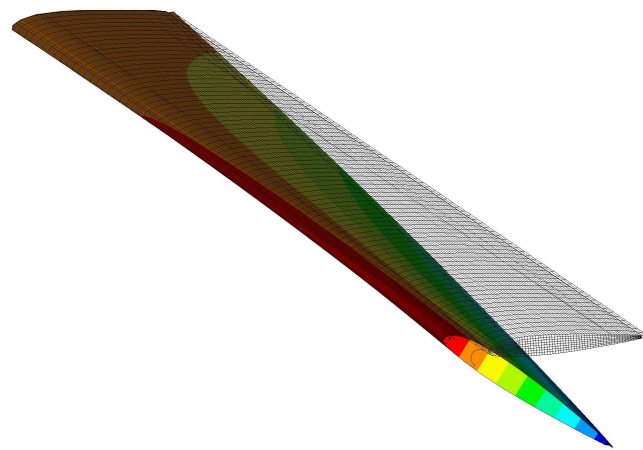


Figure 4. The twisting of a helicopter blade under the piezoelectric effect.

Determination of the centre of gravity y_{cg} and the mass distribution per unit length along the blade span m are obtained during the numerical calculation.

The location of the elastic axis y_{ea} is determined through two static analyses in which loads are applied at the leading edge (Figure 5a) and trailing edge (Figure 5b) of the structure. The elastic axis position is then determined using the displacements obtained for both loading configurations [14].

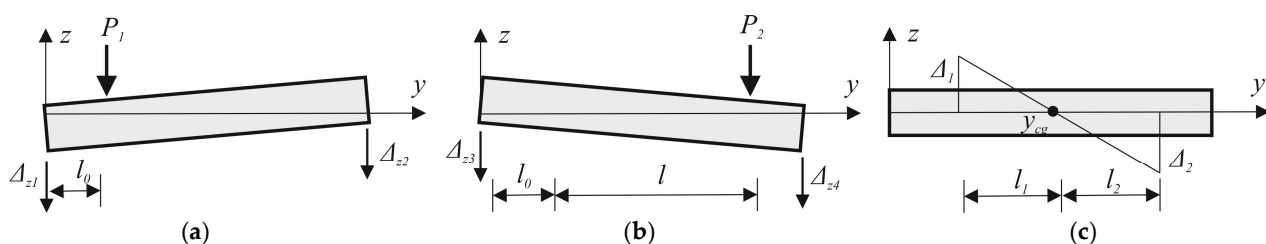


Figure 5. Schematic illustration of the procedure for determining the elastic axis location: (a) load applied on the left; (b) load applied on the right, and (c) resulting position of the elastic axis.

From the similarity of the triangles (see Figure 5c), the position of the elastic axis can be determined as follows:

$$y_{ea} = (l_0 - l_1) = l_0 + \frac{l}{1 + \frac{\Delta_2}{\Delta_1}} \quad (2)$$

The lag (L -index) and flap (B -index) bending stiffnesses are defined as follows [16]:

$$EI_{B,L} = \frac{PL^3}{3\delta}, \quad (3)$$

where P denotes the applied unit load, L represents the length of the composite blade, and δ corresponds to the resulting displacement under the unit load (Figure 6a,b).

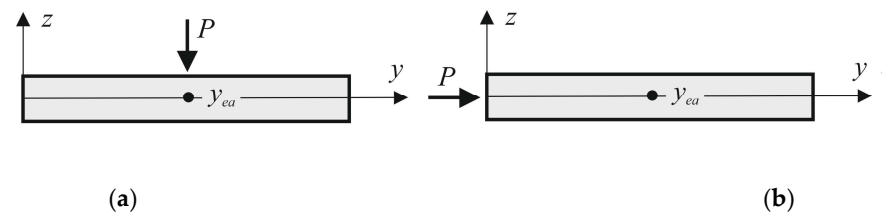


Figure 6. Schematic illustration of the procedure for determining flap (a) and lag (b) bending stiffnesses.

3. Results

To validate the numerical model, the characteristics of the BO105 helicopter main rotor blade obtained from a scaled experimental model were compared with the results of the numerical model. As shown in Table 2, most parameters agree with the reference blade. In most cases, the discrepancy does not exceed 6%. However, some deviations exist. The numerical model's lag bending stiffness is 33% higher than that of the reference model.

Table 2. Validation of the BO105 scale blade and numerical blade [17].

Symbol	Units	Scale Blade	Numerical Blade	Δ , %
y_{cg}	[% c]	25.1	25.1	0.0
y_{ea}	[% c]	20.6	20.0	3.1
m	[kg/m]	0.95	0.95	0.0
f_{T1}	[Hz]	67.9	72.03	5.7
EI_B	[Nm ²]	250	243	3.0
EI_L	[Nm ²]	5200	6905	33.0

To validate the numerical model developed, the characteristics of the BO105 helicopter main rotor blade, obtained from a scaled experimental model, were compared with the results calculated using the FEM model. As can be seen from the data in Table 2, most parameters agree well with the characteristics of the reference blade: in most cases, the discrepancy does not exceed 6%. However, some deviations were identified—the bending stiffness of the numerical model was found to be 33% higher than that of the reference model.

Figure 7 illustrates the influence of the MFC actuator placement on the torsion angle, the locations of the centre of gravity and elastic axis, and stiffness characteristics of the blade. Four numerical models of the helicopter blade were considered, depending on the type of material in the spar and the skin. Analysis of the data obtained revealed that the highest twist angle is achieved in the blade with the skin made of UD GFRP ($\sim 3.7^\circ$). The spar material does not affect the twist angle. The maximum twist angle for the models with UD CFRP skins was $\sim 1.7^\circ$ (Figure 7a). The percentage difference in the twist angle depending on the skin material type reaches 54%.

The mass distribution per unit length along the blade span increases linearly with the increase in the chordwise dimensions of the MFC actuators (Figure 7b). Since the density of CFRP is less than that of GFRP, the blade model consisting of a CFRP skin and spar has the lowest mass. A rotor blade incorporating a UD CFRP spar and skin demonstrates a lower mass relative to the baseline blade, with a reduction of approximately 24%. An increase in the chordwise length of the MFC in the baseline model of the composite rotor blade (featuring a spar and a skin made of unidirectional GFRP) leads to an approximate 24% increase in mass.

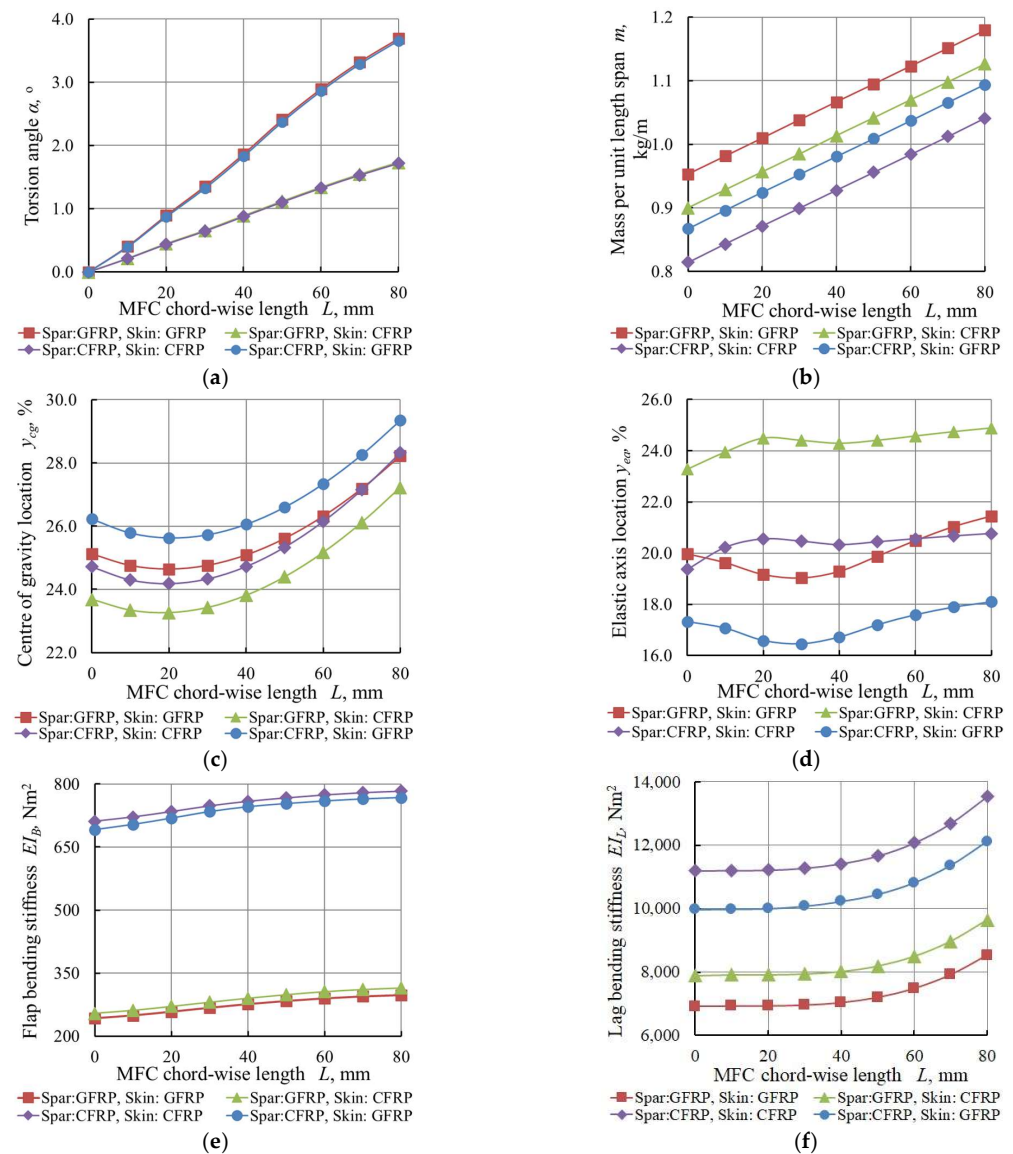


Figure 7. Influence of MFC actuators placement on the rotor blade characteristics: (a) torsion angle (α°); (b) mass per unit length (m); (c) centre of gravity location (y_{cg}); (d) elastic axis location (y_{ea}); (e) flap bending stiffness (EI_B); (f) lag bending stiffness (EI_L).

The type of composite materials for the spar and skin in the numerical model influences the initial positions of the centre of gravity and the elastic axis along the blade chord (Figure 7c,d). Figure 7c shows that extending the MFC piezoelectric actuators from the leading edge of the blade towards the trailing edge has a significant effect on the position of the centre of gravity. It should be noted that for all investigated blade configurations with MFC actuators and different composite materials in the spar and skin, the position of the centre of gravity coincides with that of the reference blade without piezoelectric actuators (see Table 2). Using CFRP as the material of the spar in the reference model increases the centre of gravity by 4%. Using CFRP as the material of the skin in the reference model decreases the centre of gravity by ~6%. In the reference model of the rotor blade, the centre of gravity firstly decreases by ~2% with an increase in MFC length and then increases by 13%.

Extending the extent of MFC actuator placement along the blade chord did not significantly affect the position of the elastic axis (Figure 7d). However, in configurations with a UD GFRP composite skin, a reduction of approximately 5% was observed when the actuators were positioned near the leading edge. In contrast, an increase of about 5%

compared to the reference case occurred when the blade surface was fully covered by MFC actuators. Using CFRP as the material of the skin in the reference model increases the elastic axis location by 16%. Using CFRP as the material of the spar in the baseline model decreases the elastic axis location by ~13%.

The influence of the MFC actuator chord-wise length along the chord on the blade flap bending stiffness is shown in Figure 7e. The blade stiffness with a CFRP spar is more than two times greater than that of the blade with a GFRP spar. The use of UD GFRP in the spar of the blade leads to an increase in flap bending stiffness by ~19%, compared to only ~10% for the blade with UD CFRP spar.

The influence of the MFC actuator chord-wise length along the chord on the blade lag bending stiffness is shown in Figure 7f. The position of the MFC actuator has no significant influence on the structural stiffness when its chordwise width is 30 mm. However, as the width of the MFC actuator increases, the stiffness begins to increase.

The influence of the chord-wise length of the MFC actuators on the lag-bending stiffness of the blade is illustrated in Figure 7f. The placement of the MFC actuators has no significant effect on the bending stiffness when their chord-wise length is 30 mm. However, as the actuator size increases, a noticeable increase in bending stiffness is observed. The increase averages between ~17% and ~19%. The figure shows that the reference blade with UD GFRP spar and skin has a lower stiffness value of 6914 Nm². The incorporation of CFRP into the skin increases the stiffness of the reference rotor blade model by ~14%. The highest stiffness is achieved in the configuration that employs unidirectional CFRP in both the spar and the skin. Overall, the stiffness difference between the reference configuration and the CFRP reinforced model reaches ~61%.

4. Conclusions

The results obtained demonstrate the influence of piezoelectric actuator placement on the performance of a model helicopter blade without changing the blade's cross-section. The numerical model was preliminarily validated against a scaled experimental model. In most cases, the discrepancy does not exceed 6%, excluding lag-bending stiffness. The skin and spar material were compared in terms of twist angle and blade performance, depending on the placement of the piezoelectric actuators. The highest value of torsional angle is observed in a composite rotor blade with MFC actuators, whether a spar and skin are made of UD GFRP or a spar made of UD CFRP materials. Using UD CFRP for the skin reduces the twist angle by almost half. The highest stiffness is achieved in the configuration that employs unidirectional CFRP in both the spar and the skin.

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