Strength analysis of the conceptual model of a main rotor blade spar with actuators

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Abstract. This paper concerns the conceptual design of a main rotor blade spar with actuators. A three-dimensional model of a main rotor blade is based on the preliminary geometric blade setting angle to increase the aerodynamic performance caused by different linear velocities of individual cross-sections. A modification of the blade setting angle results in a change of the angle of attack and influences the value of the lifting force in a given blade cross-section. The geometric setting angle was applied in designing both the main rotor blade spars and the blade. The overall dimensions of the blade depended on the available surface of the outmost blade airfoils. The important element of the designed spars was a cut in the form of a notch enabling the upper and lower crossbars of the designed spar to move during the operation of actuators. The FEM analysis was carried out on the parts of the designed blade spars. Three types of materials were compared in the finite element analysis. The internal stresses and displacements of the outmost edges of the crossbars were analyzed. The Catia V5 software was used for the designing work. The sections of the spars were analyzed using the Finite Element Method. The Pre/Post module of NX 12 was used for the FEM analysis. The displacement results were analyzed, which allowed us to determine their twist angle.

1. Introduction
The technological development of aircraft is closely related to innovative technologies, including intelligent materials. Most of the ongoing research focuses on improving the performance of aircraft, like the fixed-wing aircraft, because of their dominant position in the aviation market [1-4]. Due to the growing operational capabilities, rotorcraft are gaining more and more interest from private users, in addition to being increasingly researched and developed [5-7]. Legislation which favors the use of Unmanned Aerial Vehicles (UAVs) allows for their application in a wider and safe manner [8, 9]. It should be noted that the term "rotorcraft" means not only helicopters but also gyrocopters and unmanned aerial vehicles. The statistical analyses carried out by the Brandenburg Institute for Society and Security [10] show a significant increase in the interest in unmanned aerial vehicles, so the research and modernization of this aircraft category is an expected path of their further development.

The principle of operation of the unmanned aerial vehicles, i.e. unmanned helicopters, is similar to that of the manned aircraft and is related to the generation of the lifting force. The main element here is the rotor blade which enables the necessary maneuvers during the flight. It can be considered as the most important component of the rotorcraft. Its improvement and modification allows us to improve the aerodynamic performance. Using new technologies in rotorcraft blades [11-13], often in unmanned
aerial vehicles, as in examples [14, 15], is being investigated worldwide. Aircraft are frequently examined by bench tests [16, 17] and simulations [18-20].

The main rotor blade is a primary element, which means that a selection of design parameters is very important to achieve the optimum performance of the entire rotorcraft. The conditions of particular flight phases such as take-off, landing, horizontal flight at cruising speed or maximum speed are very different, so there are different aerodynamic expectations from the blade shape in each flight phase. Placed in the spar part of the main rotor blade, the actuators made of intelligent materials will allow us to change the shape of the blade during the flight to adjust its capabilities to the flight conditions. Aerodynamics of the blade will be modified by changing the geometric blade setting angle.

The predicted benefits of using actuators made of intelligent materials are: the possibility of adjusting aerodynamics of the blade to the flight conditions (increased thrust in hovering flight, increased flight altitude or an increased flight range), the increased lifting force, reduced power demand, decreased blade bending effect, as well as high reliability of the employed solution. This paper presents a conceptual design of a main rotor blade with the actuators made of intelligent materials. This concept design uses intelligent materials to modify the blade geometry to improve the aerodynamic performance of the aircraft.

Intelligent materials are a group of materials with special abilities so they can be used more efficiently than conventional ones. It is believed that intelligent materials are the future of technology and can revolutionize the market [21, 22] The principle of operation behind intelligent materials is the possibility to predictably modify their physical parameters by external influences. Such materials show a fast and real response time. This paper focuses on the materials that can be used in aviation, more specifically in the main rotor blade, to increase the aerodynamic performance.

The most important intelligent materials capable of improving the aerodynamic performance are the shape memory materials. Nickel-titanium alloy is one of the currently used intelligent materials. Its shape memory effect was discovered in the 1960s. The main principle of operation in shape memory alloys is based on the occurrence of reversible, thermally elastic martensitic transformation which is initiated thermally or by an external stress source. Reconfiguration of atoms results in the reconstruction of the crystal network showing a non-diffusional transformation. The nickel-titanium alloys with 49 to 57% of nickel have been practically applied in the world technological market as nitinol [13, 23, 24]. The properties of shape memory alloys enable active and fully controlled changes in the static and dynamic characteristics such as shapes, forms and frequencies of natural vibration, static deflection, resonance vibration amplitudes or damping [25, 26].

2. Methodology

2.1. Object

Figure 1 shows a view of the designed main rotor blade. The base airfoil with its section of mounting to the rotor head and its section from the base airfoil to the head is shown in Figure 2, while Figure 3 shows a view of the blade tip airfoil.
2.2. Methods
The main rotor blade has been designed using two modules available in the Catia V5 software, chiefly dedicated for supporting the entire product construction and manufacturing process. The head and base airfoil surfaces were designed in the Generative Shape Design module (surface module), whereas the profile outlines – with the Spline function. An important stage of the project was to define the guide lines (Guide) in the Multi-Sections Surface function, which enabled a linear twist of the blade. Then, a solid model of the main rotor blade and all other actions (holes, chamfers, rounds, etc.) were created from the specified surfaces in the Part Design module (solid module).

In order to perform the simulation calculations, a tetrahedral type grid was used, whose size of the computing element is 0.1 mm. This allowed replacing the solid to a numerical model consisting of 13,533,016 elements. Eight normal forces imitating four sets of actuators were placed on the first spar (Figure 4). Their directions of operation allow for parallel deflection of the upper and lower crossbar. The middle part, which is the core of the spar, is fixed. The second spar was prepared analogously to the first one. Four forces imitating the action of two actuators were applied (Figure 5). Both of them act on compression, pulling the upper and lower half bar to the central beam of the girder.

![Figure 4. Force distribution in the spar 1.](image1)

![Figure 5. Force distribution in the spar 2.](image2)

2.3. Assumptions
The designed main rotor blade is dedicated for the unmanned aerial vehicles with maximum take-off mass not exceeding 150 kg. The following initial designing assumptions for the blade were formulated: linear speed of the blade tip: 180 m/s; weight 0.5 kg; blade radius R = 1 m; distance from the rotor axis 0.15 m; airfoils: NACA 0021, NACA 0012, NACA 0006; diameter of fixing holes 10 mm; length of the head airfoil 0.115 m; length of the base airfoil 0.735 m; tip airfoil: simple rounded.

3. Results
The blade setting angle is one of the parameters influencing the aerodynamic performance. It determines the angle of attack of individual aerodynamic airfoils in the cross-section of the blade and thus the lifting force that will be generated over the entire length. The blade rotates at a specific angular velocity but the linear velocity of the individual cross-sections is dependent on their position along the blade radius.

Different linear velocities of individual blade cross-sections generate a heterogeneous lifting force. The blade speed at the beginning of the base airfoil is lower than that of the tip section. In order to distribute the lifting force over the entire length of the blade, the angle of attack of the initial airfoil should be greater than the angle of attack of the tip airfoil, which is achieved by twisting the blade. The designed main rotor blade has been preliminarily geometrically twisted. The designing assumption is based on linear twisting. The equation (1) of the straight line corresponding to the geometric blade setting angle was determined.

\[ y = -11.43x + 8 \]  \hspace{1cm} (1)

A twist angle of the last airfoil was determined as 3.43 degrees. The spars of the main rotor blade were designed in line with patent applications no. P.430431 and P.430437. Two variants of the cross-sections of the blade spars are depicted in Figure 6 and Figure 7.
The designed spars were made by adjusting the overall dimensions to the internal surface of the extreme blade airfoils. The geometric spar setting angle was also mapped in accordance with the blade setting angle. For a linear transition, two projections and guidelines were made, as shown in Figure 8 and Figure 9. The initial cross-section of the spar starts at a distance of 265 mm from the rotor axis and is twisted by 4.97°, while its final cross-section by -3.43°.

A weakened surface, i.e. a semi-circular notch (Figure 10) improves the operation of the upper and lower crossbars by means of actuators. In this model, the radius in the initial cross-section is 0.75 mm, whereas in the final cross-section it is 0.25 mm.

Figure 6. Cross-section 1; a – horizontal beam, b – vertical beam, c – top bar, d – bottom bar, e – actuator.

Figure 7. Cross-section 2; a – horizontal beam, b – vertical beam, c – top bar, d – bottom bar, e – actuator.

Figure 8. Shape of spar 1.

Figure 9. Shape of spar 2.

Figure 10. View of the semi-circular notches in the cross-sections of the spars.
Figure 11. View of the blade with spar 1 and one section of an actuator.

Figure 12. View of the blade with spar 2 and one section of an actuator.

Figure 13. View of the blade with spar 1 and two sections of an actuator.

Figure 14. View of the blade with spar 2 and two sections of an actuator.

The finite element method strength analysis was carried out for two types of the designed spars of the main rotor blade. For the analysis, the models were simplified by cutting out the selected spar areas. The analysis consists of:
- an analysis of the section of the area of the application of the actuators of spar 1:
  - displacement of the upper and lower bar,
  - stresses in the bending part (notch),
- an analysis of the section of the area of the application of the actuators of spar 2:
  - displacement of the upper and lower half bar,
  - stresses in the bending part (notch).

The MES analysis was performed using the NX 12 software in the Pre/Post module which includes extended finite element modeling tools and visualizations of results. The MES analysis was performed on three selected materials: ABS, 7057 aluminium (PA9) and C45 steel. Due to different strength properties of the materials, each of them was loaded with a different force value: 3, 20 and 40 N, respectively. Their physical and mechanical properties are presented in Table 1.

All of the analyzed elements were fixed with permanent ties on the intersection plane from the base airfoil to limit their movement in six degrees of freedom and comfortably map the working conditions. The forces were applied evenly where the actuators are based. For this purpose, a function that generates a normal force following a certain plane was used. A calculation grid of 0.1 mm cells was used in the simulations to achieve precise results. Figure 15 shows the results obtained from the stress analysis of the forces.

Table 1. Physical and mechanical properties of the materials [27, 28].

| Parameter                        | ABS    | 7057 Aluminium | C45 Steel |
|----------------------------------|--------|----------------|-----------|
| Mass density                     | 1.05*10^6 kg/mm³ | 2.66*10^6 kg/m³ | 7.85*10^-5 kg/m³ |
| Young’s modulus                  | 2*10^6 MPa   | 7.2*10^7 MPa   | 2.1*10^6 MPa   |
| Poisson’s ratio                  | 0.4     | 0.33           | 0.33       |
| Yield strength                   | 40 MPa    | 270 MPa        | 550 MPa    |
| Strength limit                   | 49 MPa    | 350 MPa        | 890 MPa    |
| Coefficient of thermal expansion | 7*10^-5 °C | 2.5*10^-5 °C   | 1.2*10^-5 °C |
| Material elongation at yield strength | 4.8 %    | 7 %           | 12 %       |
Figure 15. Stresses analysis.

Figure 16 presents the results of the displacement analysis in the form of a map of deformations generated by the acting forces. The largest displacements, parallel to the vertical axis (YC axis), are located at the edge of the crossbar.

Figure 16. Displacements analysis.

The maximum stress values for all of the cases occur as expected at the largest cut (notch). Their values are shown in Table 2. All of the considered cases do not exceed the yield point, which indicates their work within the range of elasticity. Table 2 also shows the results of the calculated average displacement of the upper bar edge and the angle of rotation for all of the cases.

Table 2. Maximum stresses, average displacement and spar angle of rotation.

| Material       | Maximum stresses [MPa] | Average displacement [mm] | Angle [°] |
|----------------|------------------------|---------------------------|-----------|
|                | Spar 1 | Spar 2 | Spar 1 | Spar 2 | Spar 1 | Spar 2 |
| ABS            | 38.83  | 20.43  | 0.4392 | 0.2434 | 3.59  | 1.99  |
| 7075 Aluminium | 268.94 | 139.90 | 0.0921 | 0.0519 | 0.75  | 0.42  |
| C45 Steel      | 547.27 | 283.62 | 0.0634 | 0.0355 | 0.52  | 0.29  |
4. Conclusions
The FEM analysis was carried out on the designed blade spars. The spars of the main rotor blades can be made of different materials, depending on their application. In this paper, the conceptual design of spars made of the materials considered for active blade control was analyzed. Three types of materials were compared in the finite element analysis. The internal stresses and displacements of the outmost edges of the crossbars were analyzed.

The internal stresses for all of the materials reached a value close to the yield strength for the spar 1 design, whereas for the spar 2 design, it decreased by about 45%. It was found from the displacement analysis that the ABS spar 2 design is the best option. The achieved displacement of about 0.5 mm twisted the crossbars (upper and lower) by an angle equal to 3.59 degrees. This is the largest displacement of all the tests. The smallest displacement was recorded for steel spar 2. The displacement for spar 2 was lesser than for spar 1 by about 30%.

Acknowledgement
This work has been financed by the Polish National Centre for Research and Development under the LIDER program. Grant Agreement No. LIDER/45/0177/L-9/17/NCBR/2018.

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