Designing and FEM simulation of the helicopter rotor and hub

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Abstract. The paper presents a preliminary design of the three-blade rotor. The geometric model was prepared in the Siemens NX 12.0 programme. After the preparation of the model and kinematic analysis, the structure was checked for strength by means of NX Nastran software. In addition, structural solutions of bearing rotors currently used in the construction of helicopters were discussed and a comparative analysis of the developed rotor design with other rotors was carried out in order to define the basic advantages and disadvantages of each solution. The main rotor of a helicopter is considered the most important component of the rotorcraft, which determines its performance. Rotating blades generate the resultant forces and moments in the rotor hub that allow the helicopter to fly. In the case of a single-rotor helicopter design, a tail rotor must be added to obtain directional control. Cyclic and collective control of blade inclination influences the generation of aerodynamic and inertial loads, which depend on the azimuthal position of the blade on the rotor disc. The number of rotor blades and the properties of the blade-hub connections strongly influence the level of load transfer from the blades through the hub to the helicopter fuselage. By incorporating a set of hinges, it is possible to reduce the component loads of the rotor, tilt and rolling moments transferred to the hull. A conventional articulated rotor head with built-in hinges requires frequent maintenance, which increases helicopter operating costs. Furthermore, a complex structure with a large number of components increases the weight of the articulated rotor.

1. Introduction
The aviation industry is the subject of numerous scientific studies, both in terms of aircraft propulsion and particular systems. Initiatives are underway to improve the rotorcraft [1, 2], and simulation studies of propulsion systems are also being undertaken [3, 4, 5, 6, 7]. Numerical fluid mechanics and other simulation methods allow advanced research to be completed in a much shorter time than required by the analytical method [8]. The possibilities of applying innovative technologies to increase the performance of rotorcraft, with particular focus on morphing technology [9, 10] or [11] are also being investigated. In recent years, the segment of unmanned aerial vehicles has been developing rapidly, as evidenced by market analyses predicting an intensive increase in the popularity of unmanned aerial vehicles [12, 13, 14] or updates of legal acts concerning UAVs [15].

This paper presents the results of numerical analyses carried out to test different blade geometries on a three-blade rotor designed for use on a research stand. The blades of the helicopter's rotor are loaded with aerodynamic and inertia forces. During the flight of the aircraft, due to aerodynamic and mass
forces, the blades make significant movements and undergo bending and torsional deformations, which in turn may cause high stresses and bending moments, especially in the blade base. Research and development projects to develop new aviation technologies typically require both the model of the test object and the equipment needed to accomplish the research.

In the scope of the implemented project aimed at developing a new concept of variable-geometry blades requires the use of a new rotor to test blades with intelligent materials. The prototype blade structure is different from the classic unmanned aerial vehicle blades. It is characterised by reduced stiffness and increased torsional susceptibility. The design incorporates systems causing additional forces generating torsional moments in the construction. Intelligent materials can also have the effect of increasing the temperature in their area of operation. These phenomena affect the performance of the rotor and other components. The design of the rotor must, therefore, curb these effects to the maximum extent.

The research analysis carried out in the field of helicopter rotor construction and maintenance shows that a rotor with a fully hinged head could reduce the interaction between the blades and the rotor to the minimum [16]. This kind of rotor consists of a head with a joint of the "Flap-hinge" type, which allows the blade to move freely in the plane containing the blade and shaft axes. The connection reduces the impact of blade interactions with each other, especially in triple and multi-blade systems. The other joint "Lag-hinge" type is a hinge that allows the blades to move forwards and backwards in the plane of rotation. The helicopter rotor is exposed to centrifugal forces that cause the Coriolis Effect in the system. The movement around this hinge reduces the effects of these phenomena. The last hinge is a mechanism for changing the blade's angle of attack. It consists of a hinge mounted along the blade axis and a pusher lever that limits its movement. Figure 1 shows a classic rotor system with articulated joints.

![Figure 1. View of a typical helicopter rotor joint system [17].](image)

2. Methodology
The rotor construction design has imposed certain restrictions resulting from the geometric dimensions of the blade. The diameter of the rotor must not exceed 2 m and the beginning of the blade base must be of the diameter smaller than 0.3 m. Moreover, smart material modules installed in the blades require an electricity supply. This requires the design and manufacture of a hollow shaft with a diameter that allows the electric wires to supply the actuators in the blades to be placed inside. The basic design assumptions of the rotor and swash plate/control disc resulting from the blade design and unmanned aerial vehicle performance are presented in Table 1.
Table 1. Design parameters of the rotor.

| Parameter | Definition | Value | Unit |
|-----------|------------|-------|------|
| \(D_w\)   | Rotor diameter | 2     | m    |
| \(N_L\)   | Number of rotor blades | 3     | pcs  |
| \(\omega_{\text{max}}\) | Maximum design rotor speed | 180   | rad/s |
| \(N_s\)   | Engine power | 30    | kW   |
| \(M_s\)   | Engine torque | 160   | Nm   |
| MTOW      | Maximum take-off weight | 150   | kg   |
| \(\alpha\) | Overtaking control | 30    | deg  |
| \(\beta\) | Longitudinal control range of motion | +/-7  | deg  |
| \(\delta\) | Transverse control range of motion | +/-4  | deg  |
| \(s\)     | General control range of motion | +/-12 | mm   |

Designing the construction of a full-joint rotor of the helicopter maintaining all the required parameters is connected with the necessity of manufacturing and selecting components of the rotor with maximally reduced overall, volume and mass dimensions. Elements such as bearings, sliding rings or lock nuts exhibit specific strength properties. For the other structural elements of the rotor, these parameters must be determined.

Guidelines for fulfilling the certification requirements are written down in the certification specification. The designed rotor, due to its dimensions and performance, is subject to the certification specification of the European Union Aviation Safety Agency: Certification Specifications and Acceptable Means of Compliance for Small Rotorcraft CS-27 [18]. As stated in CS 27.303 Factor of safety “Unless otherwise provided, a factor of safety of 1.5 must be used. This factor applies to external and inertia loads unless its application to the resulting internal stresses is more conservative.” The rotor construction must ensure a safety factor of at least \(k=1.5\).

3. Research object

The strength calculations of the designed elements are carried out using the finite element method (FEM). In this paper, the results of calculations of key elements of the designed rotor during the UAV hover operation will be presented. Numerical operations were carried out with the use of NX Nastran module, which is a part of Siemens NX 12 software. The designed solid model of the rotor with blades and control disc is shown in figure 2.

Numerical investigations were carried out for the rotor components subjected to the highest loads during operation. For this purpose, the rotor head with the shaft and swing joints with blade anchors were isolated from the solid model. The blade structure was reduced to the base and replaced by connections that allow the imposition of aerodynamic loads and inertia forces generated by the blade. The connections of the moving components and their interactions were modelled as Surface-to-Surface contact. The rigidly connected elements were modified using a Surface-to-Surface adhesive.

The strength analysis was performed for the rotating rotor at full speed and with blade configurations to ensure maximum performance. The model was loaded with equivalent forces and moments applied to the blade base due to bearing, aerodynamic and centrifugal forces, and torsional moment (figure 4). The force values are shown in Table 2.

Table 2. Loads acting on the rotor.

| Kind of load                | Value | Unit |
|-----------------------------|-------|------|
| Aerodynamic lift force      | 1500  | N    |
| Centrifugal force of the blade | 6156 | N    |
| Aerodynamic drag force of the blade | 40   | N    |
| Torque                      | 160   | Nm   |
| Rotational speed            | 180   | rad/s|
Figure 2. The three-dimensional model of the rotor prototype.

Figure 3 shows the force points and their vectors. The constraint points in the model were applied to the lower part of the shaft, restraining XY-plane displacements and Z-axis rotations. The Z-axis displacement was limited by restraining the contact surface of the shaft-locking nut and the position frame thrust bearing – the location where the rotor’s aerodynamic lifting force is transferred to the stationary position frame. The constant angle of attack of the blades and thus the direction of force acting on the individual blades were achieved by limiting the movement of the pusher lever mounting holes in the Z-axis by simulating the operation of the control disc in the hovering position.

Figure 3. Force application locations and their vectors (red vector – loads, blue vector – constraint).

The material used in the construction of the rotor is high-quality structural steel C45 (EN). In its structure, apart from the carbon content of 0.42% to 0.5%, there are also small amounts of silicon,
manganese, chromium, nickel, molybdenum, copper, sulphur and phosphorus admixtures, which all contribute to its mechanical, chemical and physical properties and strength. Due to the simplicity of machining, it is widely used in the industry. It is applied in the production of tools and machine elements that are subject to medium loads and at the same time require resistance to abrasion. This type of steel is ideal for the production of shafts and spindles, axles, unhardened gears, electric motor shafts, hubs for wheels, discs, rods, rollers and pump rotors [19]. The physical characteristics are shown in Table 3.

**Table 3. Physical properties of C45 (EN) steel in standardised state.**

| Parameter                          | Value   | Unit     |
|------------------------------------|---------|----------|
| Density                            | 7850    | kg/m³    |
| Young's modules                    | 205000  | MPa      |
| Shear modulus                      | 78800   | MPa      |
| Poisson's number                   | 0.30    | –        |
| Specific heat                      | 470     | J/kgK    |
| Coefficient of thermal expansion   | 11.1    | µm/mK    |
| Thermal conductivity               | 48      | W/mK     |

The blade yoke structure is designed using (AW-7075) aluminium alloy. It is an aluminium alloy with very high mechanical strength and high fatigue strength. It has medium corrosion resistance and is suitable for machining, polishing and grinding. Due to its properties, it is often used in machine elements and structures working under heavy loads. Given its physical and strength properties, it is widely used in the manufacture of elements in the aerospace industry [20]. Physical properties of the material are presented in Table 4.

**Table 4. Physical properties of aluminium alloy AW-7075 (EN) [20].**

| Parameter                          | Value   | Unit     |
|------------------------------------|---------|----------|
| Density                            | 2810    | kg/m³    |
| Young's modules                    | 72000   | MPa      |
| Shear modulus                      | 27100   | MPa      |
| Poisson's number                   | 0.33    | –        |
| Congealing temperature             | 475     | °C       |
| Melt flow temperature              | 635     | °C       |
| Specific heat                      | 862     | J/kgK    |
| Coefficient of thermal expansion   | 23.5    | µm/mK    |
| Thermal conductivity               | 134     | W/mK     |

The strength properties Ry (yield strength) and Ru (ultimate strength) of the applied materials are presented in Table 5.

**Table 5. Strength properties of the applied materials.**

| Material identification | Ry [MPa] | Ru [MPa] | Permissible stresses [MPa] |
|-------------------------|----------|----------|---------------------------|
|                         | k1       | k2       | k3                        |
| C45 (EN)                | 600      | 355      | 170 205 110               |
| AW-7075 (EN)            | 480      | 390      | 120 130 70                |

Bearings in the designed structure are mostly made of high carbon steel. Applied bearings have been selected from the catalogue in accordance with the manufacturer’s guidelines concerning permissible forces.
4. Simulation results
The calculations were carried out for the full model assembly. This approach makes it possible to observe the behaviour of components and their mutual interaction resulting from the forces. The key element of each rotor is the shaft, hub and pins holding the joints and blade yokes. These components are exposed to the highest loads. Figure 4 shows the distribution of stresses on the rotor shaft. The reduced stresses according to this hypothesis reach a maximum value of 17.23 MPa concentrated in the area of the lower nut securing the shaft in the bearing housing of the stand frame. The distribution of the reduced stresses is shown in figure 5.

![Figure 4. Reduced stress distribution of the shaft.](image1)

![Figure 5. The area where the highest dike-induced stresses occur.](image2)

The lifting force generated by the blades with the intelligent material actuator on the rotor caused a stress of 9.72 MPa at the top of the shaft at the point of installation of the nut holding the rotor head on the multi-purge of the shaft (figure 5). Under these forces, the shaft model was also extended by 0.0668 mm along the direction of the axis of rotation (figure 6 and 7).

![Figure 6. Distribution of stresses at the base of the head nut.](image3)

![Figure 7. Elongation of the shaft along the Z-axis.](image4)
The stresses occurring in the design of the shaft are four times lower than the permissible stresses for the material from which it will be made. The element, therefore, fulfils the certification condition with a safety factor above \( k=3 \).

The rotor head is the connecting element between all the blades and thus the forces and interactions occurring in the rotor. This element transmits the torque from the shaft to the blades via a splined connection. Damage to this component is destructive to the entire rotor. The distribution of global stresses in the model is shown in figure 8. The numerical analysis showed that the highest stresses occurred in the area of the oscillating hinge pins and reach the value of 77.08 MPa. Figure 9 shows the value of stresses in the area of mounting holes.

![Figure 8. Stress distribution of the head.](image1)

![Figure 9. Area of the highest reduced stresses.](image2)

The other important part of the rotor is the mounting yokes of the blades. In the designed rotor, due to the limited space, the construction consists of four key components: a seat element, the blade's base in the yoke, a modular bearing, a bearing housing and a pusher lever arm. The construction with a closed modular bearing allows the blade angle of attack to be changed independently of the blade force generated by the blade. The distribution of the reduced stresses is shown in figure 10. The stresses in the analysed model are concentrated mainly in the yoke part of the notch area resulting from the assembly pocket for the blade base. The highest value of these stresses is 44.40 MPa (figure 11).

![Figure 10. Reduced stress distribution on the shackle of the blade.](image3)

![Figure 11. Tensions in the notch area.](image4)

Figure 12 illustrates the stress distribution in the axial section of the yoke. The tension at the limit of the change of the seating diameter of the modular bearing and the inner surface of the first hole for the blade-mounting bolt can be distinguished here. The highest acting force is the centrifugal force acting along the blade axis. The highest displacement in this direction is 0.0087 mm (figure 13).
A pin is an element that acts as a link between the blade yoke and the rotor head. The numerical analysis showed that this particular element of the structure is characterised by the highest reduced stresses. Figure 14 shows the global stress distribution of the pin. The maximum values reached the value of 100.80 MPa and were focused in the radius connecting the bearing resistance surface with the cylindrical part of the pin (figure 15).

Stress concentration with values close to 100 MPa also occurs around the pin seat hole in the element as a "Lag-hinge" (figure 16). Axial displacements – tension due to the centrifugal force of the rotor and blade elements caused a 0.0086 mm elongation of the element (figure 17).
The last part that binds the shovel to the head is the swing joint. The steel element ensures independent blade and head displacement, eliminating unwanted stresses caused by the use of susceptible blades with intelligent materials. The distribution of reduced stresses is shown in figure 18. The value of the highest stress of 56.74 MPa was recorded within the seat of the "Lag-hinge" joint bearings. The forces transferred by the analysed element caused its deformation of 0.0050 mm (figure 19).

![Figure 18. Reduced stress distribution of the articulated components of the blade swinging joint.](image)

![Figure 19. Extension of the joint structure along the action of the blade's centrifugal force.](image)

5. Conclusions

This paper presents the main assumptions for the development of the new design of the rotor. The method of analysis and results of strength calculations of the prototype of the rotor designed for unmanned aerial vehicles using intelligent materials to modify the geometry of blades are presented. Such an application requires modification of the shaft in order to be able to supply power to the actuators installed in the blades. From the analysis, the safety factor was determined at the level of $k>1.5$, which gives grounds to obtaining certification for the strength of the design. The construction of the joint rotor has numerous moving elements in its structure. Despite the high safety factor, the places with the highest stresses, where the signs of wear and tear may appear, have been indicated. The numerical analysis showed that the element under the highest loading is the pin connecting the modular bearing of the blade yoke with the element of the horizontal oscillation joint. The stresses in this element result in a safety factor of $k=1.7$. The other analysed rotor components have a safety factor of more than 2 and in the case of the shaft; this factor is more than 3. However, it must be remembered that the structure is as strong as its weakest cell. The presented design of the rotor for unmanned aerial vehicles adapted to work with blades with intelligent materials meets the requirements for certification testing.

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