INTRODUCTION

Rotor blades should be shaped so that the maximum lift force can be achieved with the lowest possible drag force under the specified conditions. The blade twist angle is one of the factors behind the amount of the lift force generated by the aircraft rotor. The aircraft shape can be changed in various ways [1, 5, 8, 12, 14, 32]. Modifications of main rotors and blades are frequently investigated [15, 16, 21, 22, 23, 24]. Fan blades with shape memory alloy strips are examined in the paper [9]. The shape of these blades was changed by the flow temperature in a specially designed wind tunnel. The studies showed the possibility of a passive control of a car fan. The authors underlined that the materials with shape memory are gaining popularity due to high energy density and their compact design. The attention was focused on the especially attractive use of intelligent materials to improve the aerodynamic performance because other elements hindering the flow are eliminated. There are known studies on adaptive elements in helicopter blades [6], wind turbines [17] and aircraft wings [2]. The paper [6] describes the concept of using the wires made of shape memory materials as the elements strengthening a supporting structure of helicopter blades. The paper [17] focuses on the previous research and the consequences of using intelligent materials, especially a reduction of the aerodynamic drag of blades, reduction of noise and vibrations, but also the possibility of turbulence. The potential to reduce the torsional loads of helicopter blades with piezoelectric actuators by 10% was pointed out there. No moving elements, simplified designs and reduced vibration are important advantages. Numerous experiments with helicopter rotors were conducted to demonstrate the potential for load reduction. Multiple stress states that arise when the blade shape is adapted await investigation. High aerodynamic efficiency, a relatively simple design and low weight make an integration of intelligent material structures and the blade design to extend the life and improve efficiency the next stage in
The authors of the paper [2] highlight the existing compromise in the aircraft wings, which makes the performance under various conditions always sub-optimal. Changing the geometry reduces these designing compromises. Formerly, it involved additional load, complexity and costs but intelligent materials can overcome these inconveniences. Morphing is a technology, inspired by nature, dedicated to the next generation of aircraft. Unmanned aerial vehicles can provide a safe platform for testing intelligent materials which are becoming increasingly popular [7, 20, 25]. The works [28, 29] present the preliminary results of the tests of the main rotor designed to be integrated with the blades with a variable blade setting angle.

Although there have been many interesting studies and concepts, only a few aircraft using intelligent materials have been tested in a wind tunnel and even fewer have actually flown. In order to improve the aircraft performance, an alternative to morphing is to improve the propulsion systems. Despite the fact that internal combustion engines are displaced by hybrid solutions in the automotive industry, new or improved propulsion systems, e.g. Diesel engines [4], SI engines [10, 11] or Wankel engines [27] are still being tested in aviation. Furthermore, the publication [3] presents the results of research on the optimization of the wing and blade structures with active elements. The authors also referred to the studies describing the results of testing some concepts, e.g. envelope extension, increased lifting capacity or improved laminar flow. The common part of these investigations was to keep the structure stiff enough not to reduce its strength and flexible enough to modify its geometry. The paper [33] presents the research on the active control of the rotor designed for UAV aircraft. The rectangular rotor blades showing a linear twisting of 10° and with 24 actuators with active composite fiber were tested. The aim of the study was to analyze how the generated vibrations and noise are impacted by the active control of the rotor. The results show that the applied solution obviously influences the improvement of the rotor stability and performance, as well as the active blade tracking. The authors of the paper [30] present an interesting overview of the previous research on the aircraft wing that changes its shape by means of the built-in actuators, e.g. electric, shape memory, piezoelectric. The author of the paper [31] suggests that the materials which have gained in importance in aviation are fiber-metal laminates, intelligent shape memory materials and piezoelectric materials. This paper emphasizes the most important role of the composites with built-in intelligent elements in monitoring a structure condition and in controlling its properties as well as the necessity of cooperation between R&D centers and the aviation industry in this field. The application of piezoelectric materials to manufacture simple elements is under control, but their incorporation into a larger composite structure is still a subject of research. Aircraft dimensions and their complexity influence, among others, the possibilities of applying a particular solution. On the basis of this review, it can be concluded that mainly piezoelectric and intelligent materials are being considered for the aviation applications. The obtained results will enable to develop a blade susceptible to twisting by embedding intelligent materials to reduce the force required to change the blade shape and prevent the blade itself from being damaged when changing the twist angle along the rotor radius.

MATERIALS AND METHODS

The tested object is an unmanned aircraft rotor blade. Ultimately, its shape will be possibly changed by using intelligent materials. The modified parameter will be the geometric blade setting angle. The blade with an active control of the blade twist angle should show a reduced stiffness compared to the standard solutions. Figure 1 shows a model of the blade with the identified applied aerodynamic aerofoils. There is an approximation of one aerofoil to another by the multi-section solid function between each section.

The blade is based on three different NACA aerofoils which are approximated between the characteristic cross-sections as a modification of two adjacent aerofoils. Therefore, it is important to determine the transition characteristics for the derivative aerofoils between the main ones. The tested blade is divided into sections with the length of 100 mm. The first section, at the blade fixing, is shorter and represents the resultant value. Figure 2 shows the blade view with its section marked. There are 8 separate sections used for the studies. The length of each section is selected to match the estimated aerodynamic forces to the size of the wind tunnel measurement space and the range of the aerodynamic scale.
The GUNT HM 170 open-circuit wind tunnel with a closed measuring space was used for the research. This configuration causes limitations due to the interference with the walls of the wind tunnel and the horizontal pressure gradient dp/dx. The advantages of this measuring system include reduced pressure pulsation and lower flow resistance. Table 1 shows the basic parameters specific to the wind tunnel. Figure 3 shows the view of the test stand.

A wind tunnel is a classic device for flow testing in aerodynamic experiments [18, 26, 34]. The tested object remains stable during air movement. The desired flow is generated around the object. The GUNT HM 170 is an open wind tunnel to measure the aerodynamic parameters of different models. The maximum air velocity that can be achieved in an open wind tunnel is 28 m/s. The wind tunnel is equipped with a two-component aerodynamic scale.

Figure 4 shows the wind tunnel measurement area prepared for testing. There is the sensor of the thermoanemometer mounted on the extension arm and placed in the working space, in front of the examined blade section. The thermoanemometer module ATU 08 is used in the tests (Figure 5). Thermoanemometric study is an indirect method of measuring the flow velocity of gases by calculating the heat loss of the warmed element placed in the tested flow. The sensor measuring element is a fiber of several micrometers in diameter, made of a temperature-dependent resistance material. Electric current heats up the fiber, so its temperature is measured simultaneously. The ATU 08 four-channel eight-path constant-temperature and direct-current module is designed for precise laboratory measurements of speed and temperature in air flows [19].

The test stand enables: measurement of air flow velocity, adjustment of the angle of attack, measurement of the lift and drag forces as well as measurement of the ambient air temperature. The aerodynamic forces were measured using a two-component aerodynamic balance, which is part of the wind tunnel equipment. The balance is used to measure the components of forces parallel and perpendicular to the direction of air flow. The method of forces measurement on an aerofoil as a function of angle of attack is shown in Figure 6.

### Table 1. Parameters of the GUNT HM 170 wind tunnel

| Parameter                              | Value             |
|----------------------------------------|-------------------|
| Flow cross-section (width x height)    | 292 x 292 mm      |
| Length                                 | 450 mm            |
| Maximum velocity of wind               | 28 m/s            |
| Pressure difference                    | 500 Pa            |
| Maximum volumetric flow                | 9000 m³/h         |
| Power of the electric engine           | 2.25 kW           |
| Maximum fan velocity                   | 2850 obr/min      |
| Force measurement range                | 0...5 N and 0...10 N |
Fig. 3. Test bench: 1 – measurement space, 2 – scales display, 3 – thermoanemometric module, 4 – computer with a data recording device

Fig. 4. Measurement area: 1 – thermoanemometer, 2 – tested blade section, 3 – aerodynamic scale

Fig. 5. ATU 08 module [19]
Fig. 6. Measurement of the lift and drag forces on an aerofoil as a function of angle of attack [13]

Fig. 7. Lift force coefficient for all velocities
RESULTS

The correlation between the lift force coefficient and the angle of attack for all the tested velocities is shown in Figure 7. The values of the coefficients were determined with reference to the angle of attack \( \alpha \) the value of which – amounting to 0 – corresponds to the initial position for the tested blade. The impact of the angle of attack on the lift force coefficient for eight examined blade sections at four air flow velocities is presented. The highest value of \( C_z \) at the air flow velocity \( v=5 \text{ m/s} \) was obtained for section 8 at the angle of attack \( \alpha = 14^\circ \). Sections 1 to 8 reach their maximum values for the angles: 4°, 4°, 6°, 10°, 10°, 12°, 14°, 14°. The highest \( C_z \) value at the air flow velocity \( v=10 \text{ m/s} \) was obtained for section 4 at the angle of attack \( \alpha = 14^\circ \). The sections reach their maximum values for the angles: 8°, 10°, 14°, 14°, 14°, 16°, 16°. The highest \( C_z \) value for velocity \( v=15 \text{ m/s} \) was obtained for section 3 at the angle of attack \( \alpha = 14^\circ \). The sections reach their maximum values for the angles: 8°, 10°, 12°, 14°, 16°, 16°, 16°, 16°. The highest \( C_z \) value for velocity \( v=20 \text{ m/s} \) was obtained for section 3 at the angle of attack equal to \( \alpha = 12^\circ \). The sections reach their maximum values for the angles: 8°, 10°, 12°, 14°, 16°, 16°, 18°, 16°.

Figure 8 illustrates the correlation between the drag force coefficient and the blade twist angle for all the analyzed velocities. The highest drag force coefficient was found in each case for the first section which includes the blade head. Section 7 has the lowest drag force coefficient for all of the examined velocities and angles of attack. It is worth pointing out that for velocity \( v=10 \text{ m/s} \), the drag force coefficient did not exceed 0.15 at any time. Basically, as the angle of attack increases,
the value of drag force coefficient also becomes higher. The change of the drag force coefficient is irregular for velocity $v=5\text{ m/s}$. The change is too little to be measured with the balance.

Figure 9 presents the influence of airflow velocity on the characteristics of the lift force coefficient $C_z$ as a function of the angle of attack. The characteristics were performed for each of the examined blade sections. The increase in the airflow velocity is accompanied by the increase in the angle of attack at which the maximum value of $C_z$ occurs. The highest values of $C_z$ occur at the higher airflow velocities.

Figure 10 illustrates the impact of airflow velocity on the characteristics of the drag force coefficient as a function of the angle of attack. The experimentally determined characteristics are presented for each of the examined blade sections. Basically, as the angle of attack increases, the value of drag force coefficient also becomes higher. The change of the drag force coefficient is irregular for the smallest analyzed velocity $v=5\text{ m/s}$. The drag force coefficient is lower at the higher airflow velocities in a given range of angles of attack. For blade sections 1–4, the drag force coefficient takes the lowest values in the range of $-8\pm0°$. In the following sections (5 to 8), the lowest values are taken in the range of $-4\pm4°$. The drag force coefficient in these ranges does not exceed 0.10 in each section. The lowest values of the drag force coefficient within the analyzed range of angles of attack were achieved in section 7. The largest ones are found in sections 1 and 2 and exceed the values of 0.3 for the angle of attack of 20°.

A sample analysis of the drag force coefficient was conducted for section 3. Figure 11 shows the functions approximating the correlation of the drag force coefficient and the blade twist angle for the specific velocities and the equations describing them. The second degree polynomial was appropriate in each case. Except for the lowest air
flow velocity at which irregular courses were obtained, the lowest drag force coefficient value was obtained for the highest velocity. This trend appears in most of the examined sections.

An important parameter informing about aircraft performance is the lift-to-drag ratio $k$ which is determined from the formula:

$$k = \frac{C_z}{C_x}$$

where: $C_z$ and $C_x$ – aerodynamic coefficients of the lift force and drag.

For the optimum angle of attack, the maximum lift-to-drag ratio is achieved. This property is specified for the designed main rotor blade by determining the lift-to-drag ratio $k$ for particular blade sections and four wind tunnel airflow velocities (Figure 12). For $v=5$ m/s, the value of $k=6$ was exceeded in section 8 only; at $v=10$ m/s, the maximum value of 7.33 was achieved in section 7. For $v=15$ m/s, the lift-to-drag ratio deteriorated but homogeneous results were obtained for $k=5÷7$ in all the sections, except the initial ones, in the range 4÷16° of the angle of attack. The highest lift-to-drag ratio, i.e. $k=7÷8$ was achieved at $v=20$ m/s for sections 6÷8.
CONCLUSIONS

The individual sections show noticeable differences in the aerodynamic coefficients due to a different blade twist angle along the blade length. By treating the zero blade angle position as a reference for particular sections, the most favorable setting for the entire blade can be specified. Theoretically, in order to achieve the greatest lift force, the blade should be twisted so that its individual positions would be at these angular settings. While analyzing the obtained results, it can be observed that for the same air flow velocity, the highest lift force is generated by section 3 for $\alpha = 12^\circ$.

The lowest value is generated by section 1 because this section is the part of the blade connected to the head and does not generate the lift force so effectively over its entire length. The blade tips are based on aerofoils which also exhibit deteriorated properties compared to the best section. Section 1 generates 25% lesser lift force than section 3, while section 8 generates 16% lesser lift force than the best section 3. Actually, the position according to the maximum lift force is not necessarily required at this stage due to the aero-elasticity of blades under real conditions. The tip cross-sections of the blade reach their optimum for higher angles of attack due to the aerodynamic forces, inertia forces and elastic reactions of the overflown blade. They will be deformed during operation, which will lead to an increase in their angle of attack relative to the initial position.

Fig. 12. Lift-to-drag ratio for all velocities
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