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DETERMINATION OF LOADS IN THE ULTRALIGHT HELICOPTER BLADES

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Abstract. The article describes research that was carried out on coaxial a single-seat ultralight helicopter Rotorschmiede VA-115 which is manufactured by German firm RS Helikopter GmbH. The purpose of the work was to determine the blades' loads necessary for further blade fatigue analysis and ground bench tests. The methodology for the load determination consisted of deformation measurements using strain gauges in various flight modes from hovering to maximum speed flight, including climb, descent, acceleration, and braking. Ultralight helicopters occupy the smallest cost niche and, as a rule, full-fledged fatigue studies are not performed for such helicopters. The requirements for ultralight helicopters are also quite loyal, allowing them to pass such experiments. Analysis of the data shows that the amplitude of bending moments on the lower rotor is higher by 1.2 to 2 times the value on the upper rotor. The absolute maximum value of the bending moment is significantly greater at the minimum weight, although the oscillation amplitude becomes smaller. The presented data can be useful for designers of ultralight and UAV helicopters with teetering hinge rotors.

Keywords: ultralight helicopter, main rotor, blade, flight, tests.

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Introduction

Ultralight helicopters occupy the niche of the simplest and cheapest aircraft. The size and cost limitations of helicopters of this class often do not allow for full-fledged testing, in compliance with the procedures specific to large aircraft. In particular, strain gauge tests of the rotor system are often not fully done for fatigue evaluation. Under these conditions, manufacturers limit themselves to some simplified tests. In addition, airworthiness standards specific to ultralight helicopters are also quite loyal in many countries, which helps to avoid several complex procedures. Because of these reasons, there is little information available on the testing of rotor systems for little rotary vehicles. At the same time, such data is necessary for designers of small manned rotorcrafts and UAVs using a rotor system with a common teeter hinge.

The purpose of the work was to determine the loads in the blades during the different modes of flight. It's necessary for further blade fatigue analysis, ground bench tests, and establishing the lifetime of blades. The methodology for the load determination consisted of deformation measurements using strain gauges in various flight modes from hovering to maximum speed flight, including climb, descent, acceleration, and braking. It allows coverage of typical loads at all flight modes (Mikheev, 1987).

Generally, ultralight helicopters are classified as rotorcraft with a maximum takeoff weight of 450 to 600 kg (Dudnik & Karabut, 2023). This indicator varies depending on the requirements of a particular state (Losev et al., 2007; Grebennikov et al., 2013). The loyalty of the requirements for ultralight helicopters is due to the low potential danger of these vehicles to other people and the environment. The capacity of these rotorcrafts is 1–2 people. However, often 2 seat helicopters can lift two people with only a small weight, especially in hot climates. These helicopters have a low rotor tip speed and, accordingly, a high relative load capacity per power. As a result, their maximal horizontal speed is insignificant and does not exceed 200 km/h, and in many cases less than 150 km/h. Despite the simplicity of requirements for ultralight aircraft, manufacturers must be aware of the fatigue limits of the components of small helicopters. First of all, the requirements for determining fatigue strength relate to blades. Of course, the determination of fatigue strength must be done by the loads that may occur on a helicopter in flight conditions. Due to their small size, ultralight helicopters are stored in closed hangars and therefore weather conditions are not affected them during the ground standing (Kargaev & Ignatkin, 2019).

Unfortunately, there are very few studies on ultralight helicopters, so it is very difficult to find information about the loads in this class. This class of rotorcraft exists somewhat apart from vehicle classes corresponding to the CS-27 and CS-29 requirements.

1. Research object, investigation methodology and measuring equipment

The research was carried out on a single-seat ultralight helicopter Rotorschmiede VA-115 which is manufactured by German firm RS Helikopter GmbH (Figure 1), the maximum take-off weight of which is 275 kg. The rotor system consists of two coaxial rotors with, a diameter of 4.5 meters. The rotor hubs have a common teeter hinge. Rigidly fixed blades with each other lead to the fact that there is always a bending moment on the blades and it is the greatest in the root part. The helicopter was designed according to LTF-ULH requirements (Deutsche Flugsicherung, 2019).

Generally, the methodology for determining the blade fatigue characteristics included:

- determination of blade loads in all typical flight modes,
- determination of equivalent stresses in the blade,
- performing of the blade fatigue parameters investigation on the ground bench using the parameters determined in-flight experiments.

This article describes only the first stage of this research. At this stage, the flight modes were determined, flight tasks were synthesized, parameters recording was initiated, and the flight was performed in accordance with the task. After the flight, the data was transferred to processing.

The measuring equipment of the helicopter included three modules, two of them were mounted on the rotors and rotated together with the rotors. Despite the small dimensions of the helicopter, the installed modules made it possible to record several parameters on rotating modules: the torque on the shafts, bending moments on the blades, and the force in the blade pitch horn with a 625 Hz frequency. The force in the blade pitch horn was converted into the torque in the root part of the blade.

Figure 1. Ultralight helicopter VA115 with an installed measuring system (RS Helikopter GmbH)

Strain gauges were installed according to the half-bridge scheme to measure the moments in the plane of rotation and the vertical plane. A measuring system has already been used on an ultralight rotorcraft (Rapp & Wedemeyer, 2000; Feil et al., 2017). VA115 measuring system was configurated to the task of measuring the loads in the blade during the flight. The data was accumulated on the disks and read out after the flight. The reliability of data acquisition was higher, however, this required the identification of the beginning and end of the mode at the stage of data processing.

2. Measured parameters

Data on the blade loads in all possible flight modes are required to determine the resource of the rotor system. This makes it possible to estimate the total damageability of the element structure. Single-seat ultralight helicopters cannot perform cost-effective aviation work but are actively used for entertainment and piloting skills training by experienced pilots. An analysis of the flight scenarios for an ultralight single-seat helicopter made it possible to determine the time during which the helicopter will be in a given flight mode. The analysis was partially based on statistical data for little weight helicopters. The results of the analysis are presented in Table 1.

Table 1. Calculated relative flight time of an ultralight single-seat helicopter

№	Flight mode	Relative flight time, %
1.	Braking	1
2.	Maximum speed	2
3.	Cruising speed	50
4.	Hovering with the maximum load	22
5.	Hovering with the minimum load	22
6.	Acceleration	3

The presented data make it possible to determine the equivalent bending moments of the blade. The value of the equivalent moment can be determined by the summation formula (Mil, 1968; Mikheev, 1987):

$$M_{\Sigma} = \sqrt[3]{\sum_{1}^{n} M_i^3 \overline{t}_i}, \tag{1}$$

where M_i – the bending moment of the blade in a specific flight mode, $\overline{t_i}$ – relative flight time in the mode, n – the number of flight modes in which the tests were carried out.

Following this equation, the average values and amplitudes of equivalent moments in the vertical and horizontal planes are determined, which can later be used to determine the blade resource.

Based on the required flight conditions, a list of flight modes was determined in which measurements should be performed. These should be flights at different speeds, from hovering to maximum speed, climb, descent, acceleration, and braking. The climb and descent were not set separately and were evaluated when flying at speed. Braking at low speed and flying at maximum speeds can give maximum loads (Mil, 1968). In accordance with this, recorded flights were carried out in the following modes (Cooke & Fitzpatrick, 2002; Aleksandrin et al., 2007):

- Hovering;
- Acceleration;
- Braking at low speed;
- Flying at maximum speed;
- Flying at cruising speed.

The mode was determined by the magnitude or change of the horizontal velocity. The takeoff weight ranged from a minimum of 225 kg to a maximum of 275 kg. Flight mode recordings were repeated.

A conservative approach was used to determine the loads. According to this approach, the maximum recorded loads are used for further analysis of the resource. With this approach, the values can be great, since wind gusts and other temporary factors can affect them, which can lead to the appearance of excessive loads during the flight.

3. Measurement results

It was expected that high loads would occur in the modes of rapid braking at low speed. In this regard, special attention was paid to this test. These maneuvers were repeated several times. The speed changes are shown in Figure 2. At the final moment of braking, a negative airspeed was observed, even though the helicopter did not fly backward. This phenomenon was caused by the movement of the rotor inductive airflow in the direction of flight.

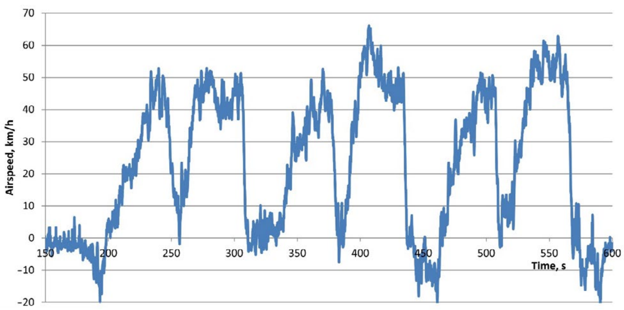
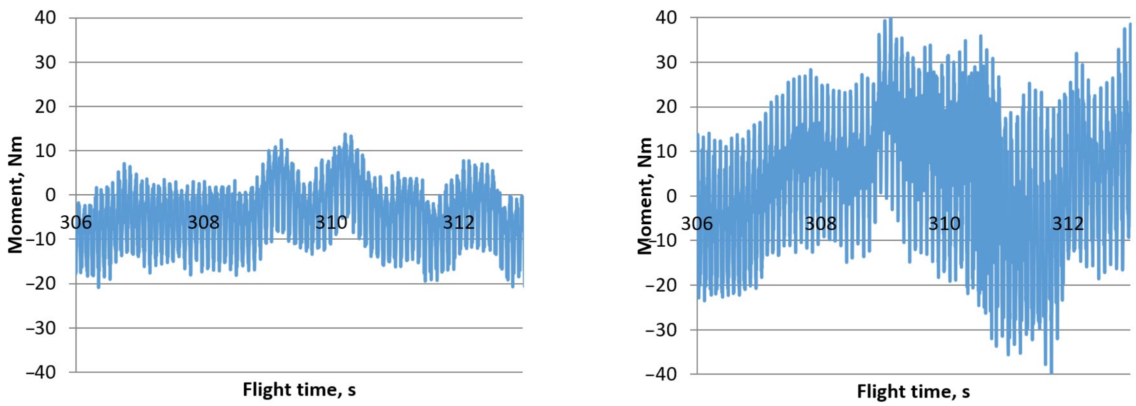


Figure 2. Recording airspeed parameters during the braking at low-speed flight

Analysis of the data performed on the example of braking (Figures 3, 4) shows that the amplitude of bending moments on the lower rotor is higher by 1.2 to 2 times the value on the upper rotor. The big difference relates to the bending moment in the horizontal plane, while the small difference relates to the moment in the vertical plane. The reason for such a moment difference is the presence of the lower main rotor in the wake of the upper rotor (Petrosian, 2004). The interaction of the lower rotor blades with the inductive airflow from the upper rotor leads to an increase in the bending moments in the blades. The upper rotor did not have higher loads in any modes. Thus, the loads on the lower rotor are more conservative for the blade lifetime prediction of the coaxial helicopter. This loading was used in further calculations. The data of the moments on the modes were collected in a general table of parameters for further summation according to Equation 1. The bending moment in the plane of rotation is 3–4 times greater than in the vertical plane due to the absence of a horizontal hinge, but the section modulus in this plane is 10 times greater. In this regard, the influence of this moment on the resource of the blade is not so critical.

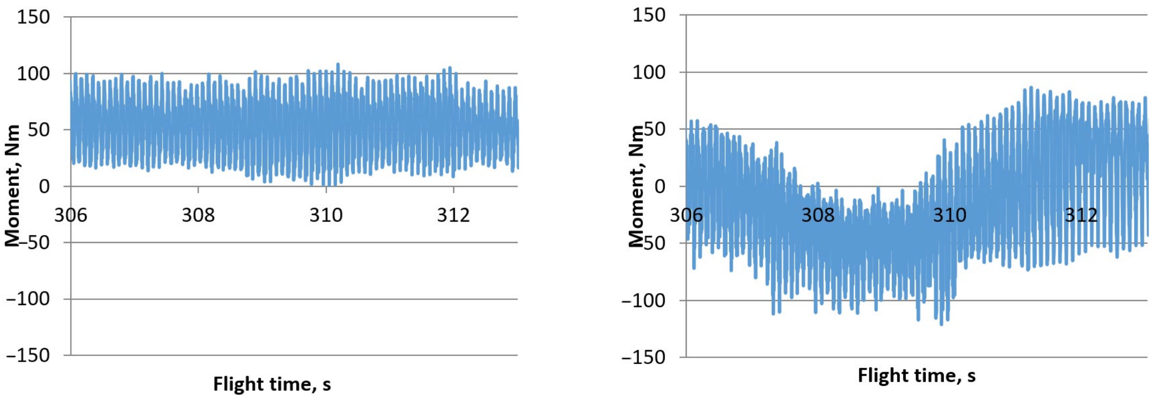
The amplitude-frequency analysis of bending moments (Figure 5) shows that a low level of bending moments is observed while keeping a constant operating engine RPM. It indicates the absence of resonant phenomena in the blade in the operating mode. The third harmonic, visible in Figure 4, was practically not visible in other measurements.

The hover measurements with various payloads showed that the moments, in this case, are very dependent on the takeoff weight of the helicopter. The helicopter has two blades on each rotor, which are connected to each other rigidly on the hub. The cone angle was chosen according to the average takeoff weight. During the hovering with a minimum weight, the blades will bend



a) b)

Figure 3. The bending moment on blades in the vertical plane during the fast braking: a – upper rotor; b – lower rotor



a) b)

Figure 4. The bending moment on blades in the horizontal plane during the fast braking: a – upper rotor; b – lower rotor

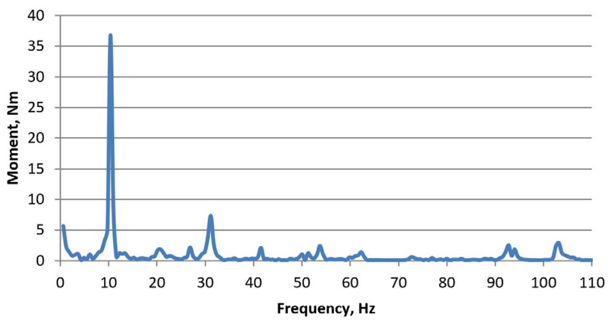


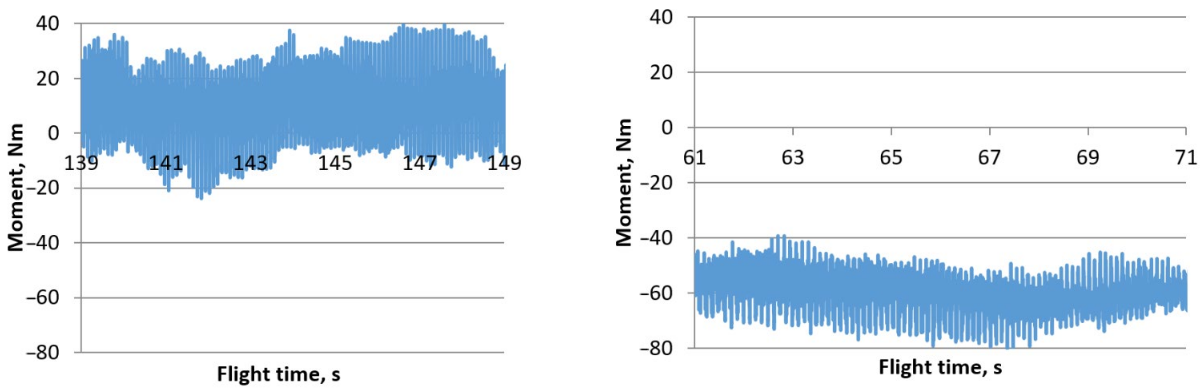
Figure 5. Frequency analysis of the moment in the rotational plane of the lower rotor during braking

down, and with a maximum weight, up. With an average helicopter weight, their position is directed along the total vector of aerodynamic and centrifugal forces. However, at maximum weight, the aerodynamic force equal to the weight of the helicopter increases and bends the blades up. At minimum weight, the aerodynamic force decreases and the centrifugal force bends the blades down. Accordingly, the moment changes its magnitude and sign. This can be seen in Figure 6. The absolute maximum value of the bending moment is significantly greater at the minimum weight, although the oscillation amplitude becomes smaller. A significant increase in the amplitude with increasing takeoff weight exists for the bending moment in the rotational plane and at the blade torque. Generally, the blade torque has a very small value in hover, as can be seen in Figures 7, 8. Tests on other modes have shown that this trend persists in them as well.

Flight records in other modes associated with horizontal flight speed showed that significant loads on the blades occur at maximum speed, as expected. The most conservative values from horizontal speed flight were used for calculations. Limit loads for various flight modes are shown in Figures 9 and 10.

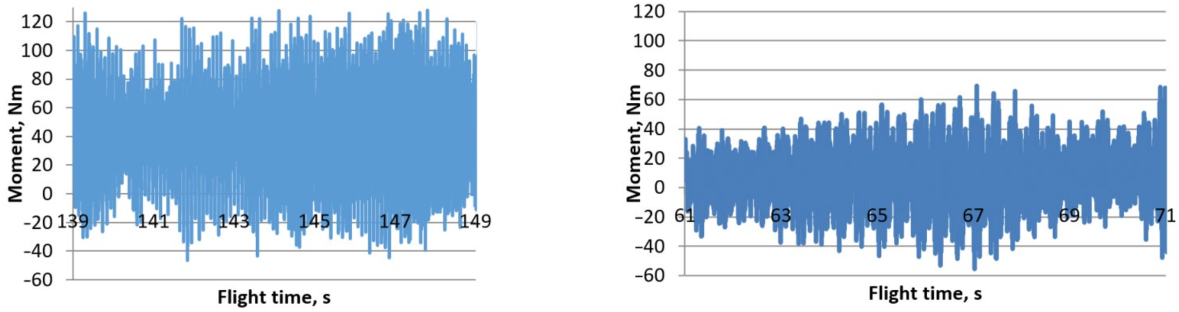
It can be seen that the bending moment amplitude in the vertical plane varies from 16 to 29 Nm at the maximum weight of the helicopter and from 21 to 34 Nm at the minimum. The values are close, which means that the weight change has little effect on the parameters of the variable component of the load. The smallest value of the amplitude is observed in the hovering mode, while the average value of the bending moment, is the largest in hovering.

The average value of moments for the minimum and maximum helicopter weights have the opposite sign. For maximum weight, this is from 18 to 43 Nm. For the minimum weight, the load range is slightly smaller, ranging



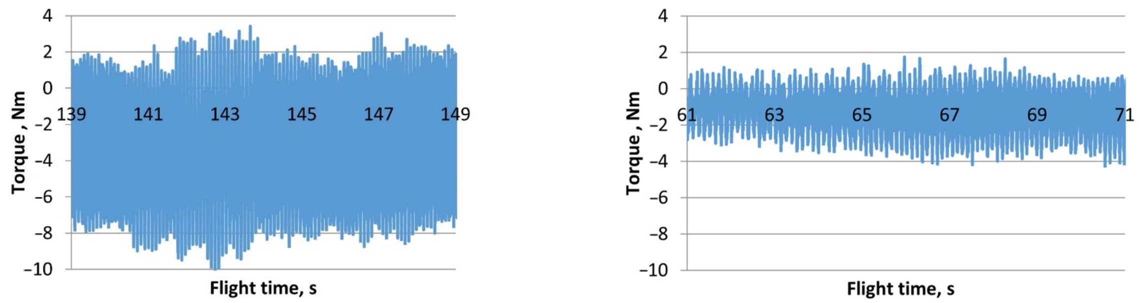
a) b)

Figure 6. Bending moment of the blade in the vertical plane at hovering: a – Max takeoff weight (TOW); b – Min TOW



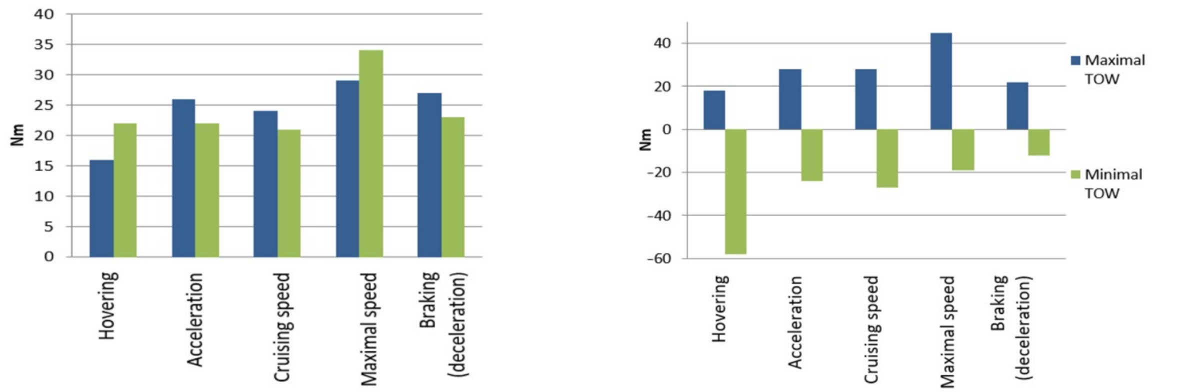
a) b)

Figure 7. Bending moment of the blade in the rotational plane at hovering: a – Max TOW; b – Min TOW



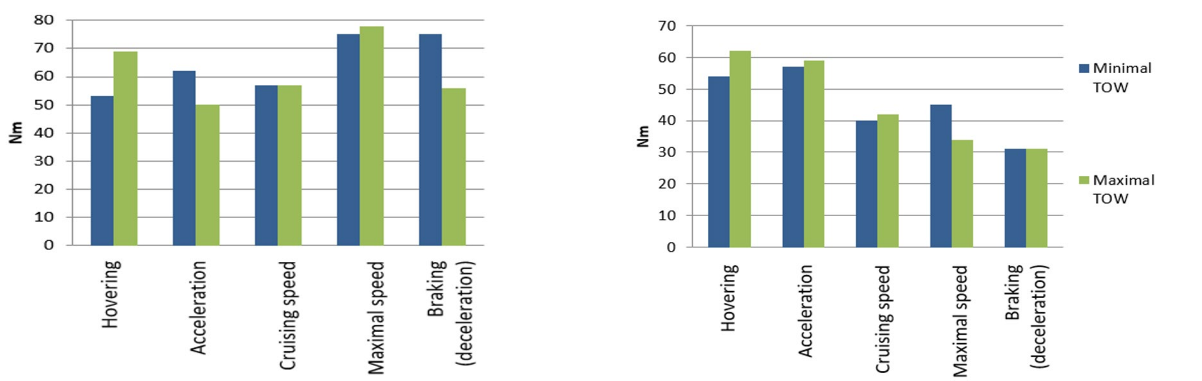
a) b)

Figure 8. Blade torque at hovering: a – Max TOW; b – Min TOW



a) b)

Figure 9. Bending moment of the blade in the vertical plane. Results of flying tests: a – Amplitude; b – Average value



a) b)

Figure 10. Bending moment of the blade in the rotational plane. Results of flying tests: a – Amplitude; b – Average value

from –11 to –26 Nm. Only in hover mode is the blade deflection greater and is –57 Nm. In all modes, the blade bends down due to the small vertical component of the blade load. The presented cases of loading are limiting for the constant component of the bending moment. With other takeoff masses, the blade deflections will be closer to the neutral value and, accordingly, the bending moment in the vertical plane will be less. Thus, amplitude loading is the main one for a vertical plane moment.

The bending moment in the plane of rotation has 2 times greater values for the variable and the constant components. However, the moment of inertia of the blade section in the rotational plane is 8 times larger than in the vertical plane, accordingly, the magnitude of the bending moment in the plane of rotation is not so critical for evaluating the helicopter blade.

The presented data make it possible to determine the equivalent bending moments of the blade, which can be used for further testing of the blades on a fatigue bench.

Conclusions

The obtained load results allow to determine the resource of the helicopter blade. The novelty of the research lies in the fact that detailed measurements of the blades of ultralight helicopters in flight were carried out. As a rule, ultralight helicopters are not tested in different flight modes. This is due to the loyal requirements of airworthiness standards for ultralight aircraft and their low cost.

The greatest loads on the blades of a coaxial helicopter are observed on the lower rotor. Its values must be taken into account when performing calculations. An increase in the takeoff mass of the helicopter leads to an increase in the amplitude of the bending moment oscillations, while the average value of the moment in the vertical plane can be either positive or negative, depending on the takeoff weight. This is typical for helicopters with a common teeter hinge. The torque of the blade is very insignificant and practically does not affect the lifetime.

Sharp maneuvers and atmospheric impacts generate short-term non-fatigue failures. However, there was very little possibility of such phenomena and their influence on the blade life cycle. It takes into account by safety factors.

The performed tests included the main flight modes inherent in an ultralight helicopter. This allows to determine the loads and cycles for the fatigue performance of the blade. The determined values were used for the theoretical calculation of the blade resource and performance of blade life tests on a special bench. Such a bench was developed further. The bench simulated a constant centrifugal force and an equivalent cyclic load on the blades, determined from the research results. According to the results of calculations and bench tests, it was confirmed that the life cycle of the blade exceeds the planned life cycle of the helicopter.

The presented data can be useful for designers of ultralight helicopters to predict loads in the rotor system.

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