TRANSPORT PROBLEMS 2024 Volume 19 Issue 3
PROBLEMY TRANSPORTU DOI: 10.20858/tp.2023.19.3.07

Keywords: blade; fatigue; composite material; helicopter

Vitaly DUDNIK[1]

LIFETIME DETERMINATION OF ULTRALIGHT HELICOPTER BLADES

Summary. Determining the guaranteed operational time of helicopter blades is one of the important tasks necessary for successful vehicle use. Flight tests on different modes and special fatigue benches are used to solve such problems. The loads recorded during the flight are applied to ground tests on a bench. The ground fatigue tests of the ultralight helicopter blades have features associated with the influence of the scale factor comparison with the big helicopters. These features are presented in this article as the example of a ground test for a VA115 helicopter blade and a method of recalculating data. The purpose of these tests was to confirm the guaranteed service life of blades and define a reliable method for it.

1. INTRODUCTION

Ultralight helicopters are designed and produced in different countries. They can be single or double seats [1] and perform the function of individual vehicles. Their empty weight can range from 115 to 400 kg. Often, the rotor system and transmission of vehicles of this class are used for the manufacture of unmanned helicopters, so these studies may be interesting to manufacturers and users of unmanned rotorcraft. One of the most important issues for a helicopter is the guaranteed time of reliable operation of the blade. This is important to know for both aircraft companies and government agencies responsible for flight safety.

The admission to flights of ultralight helicopters in different countries is carried out according to the national requirements of the countries. These requirements may vary significantly. One of the most strong is the German LTF-ULH standard [2]. These requirements demand confirmation of the reliability of the ultralight helicopter and among the blades. As a rule, ultralight helicopters do not have significant flight hours per year, so they are designed for relatively small operational times compared to helicopters of larger weight categories. In particular, the purpose of the presented test was to confirm the guaranteed service life of 1000 hours for the blades. The problems of creating a bench for fatigue testing of the ultralight helicopter blades and determining the guaranteed operational time of the blade were solved to achieve this purpose.

Of course, such benches have already been created in different countries. They have different structures and parameters. In the most popular approach, tests are carried out for one blade that is fixed rigidly in the root part. Centrifugal forces are simulated through a system of sling tensioners with a hinge connection [3]. Transverse loads are applied with resonance frequency. Resonance allows high values of blade deformation to be obtained at the lowest power consumption. Another bench structure is also used in which the blade is hinged to the bench and rigidly connected to a movable sling system [4]. In this case, it is easier to simulate the load in two planes and the torque. However, when the blade deflects in the vertical plane, there is a significant influence of the longitudinal tension force, which simulates the centrifugal force to transfer force. As a result, a vertical component from the tension force appears, and thus, the vertical force activator begins to counteract the longitudinal force activator. At the same time, it becomes difficult to simulate flight loads on the bench.

[1] Silesian University of Technology, Faculty of Mechanical Engineering; Akademicka 2A, 44-100 Gliwice, Poland; e-mail: vvdudnik812@gmail.com; orcid.org/0000-0002-5798-8019

In this case, it is proposed to use a two-blade system. Such a system has been acknowledged, but it has not been used for small helicopters since a bench of this design requires large dimensions and a significant mass of material. Its advantages are the simulation of flight loads, with negligible application of transverse loads, and a significant reduction of testing time. However, benches with two blades have been used for medium and heavy helicopters, and the scale factor did not have a significant effect. This study presents an attempt to apply the described approach to testing the blades of one of the lightest manned helicopters in the world.

2. LOADS ON ULTRALIGHT HELICOPTER BLADES

An effective procedure for determining the guaranteed operational time consists of two main stages. During the first stage, the loads on the rotor system are determined at different flight modes [5, 6, 7]. These tests must include maneuvers that may occur in flight, even for short periods. These may include, for example, sudden braking. Bending loads on each blade occur at the first harmonic frequency, repeating with each revolution of the rotor. The second and higher harmonics have much smaller values. The higher harmonic loads are practically non-existent compared to the first harmonic load if the blades are rigidly connected in a teeter hinge rotor system. Ground fatigue tests are performed using the obtained loads at the second stage. The operational time of the helicopter's rotor system can be determined based on the test results. Similar methods are used for larger helicopters and extremely rarely for ultralight rotorcraft. The use of this approach is difficult due to problems of the significant work intensity of the procedures and the scale factor inherent in the ultralight aircraft.

In this case, the blade fatigue analysis, according to the described method, was carried out for one of the smallest aircraft in the world: a single-seat VA115 helicopter manufactured by RS Helicopter GmbH (Fig. 1). The maximum take-off weight of this aircraft is 270 kg, and its rotor diameter is 4.5 m. The helicopter has a teeter hinge rotor hub. The blades have unsymmetrical airfoil and are rigidly connected one to another. The strength structure consists of the C-shape spar and skin from composite materials. All layers of them were made from carbon fiber (CFRP). The skin supports the right aerodynamic shape and withstands torsion. The layers of skin have a fabric with direction ±45º to the longitudinal axis of the blade. The spar of the blade is done mainly from the fiber of 0º. The internal space is filled with foam. There are also lead weights at the leading edge of the blade.

The recording equipment was used to determine the loads on the blades during the first stage of tests. It consists of three parts: a part rotating with the upper rotor, a part rotating with the lower rotor, and a part fixedly mounted on the fuselage. The moments on the blades were determined using strain gauges glued to the root of the blade in both the horizontal and vertical planes. Torque is determined through the tension loads in the pushrod to the blade pitch horn. During flight experiments, bending moments and torques on the blades were determined at different flight modes. The greatest bending moment was in the root part of the blade for the teeter hinge rotor system [8, 9]. In this regard, measurements were carried out near the place where the blades were attached to the hub (Fig. 2).

The magnitude of the loads depends on the task performed by the helicopter. One of the heaviest cases of blade loading is during training flights. In these flights, the helicopter spends a significant amount of time in hover and low-speed mode, when the required engine power is close to the maximum value. An example of the loads on the blades is shown in Fig. 3. More detailed experimental data are presented in [10]. Only the load data of the lower rotor is considered when executing the fatigue test. It was used in accordance with a conservative approach. The reason for this is that the loads on the lower rotor during the tests were greater or equal to the loads on the upper rotor in all flight modes. The measured values of bending moments in the root part of the blade are shown in Table 1. The torque of the blade had a very small value and was not considered in further calculations. The centrifugal force did not depend on the flight mode since the rotor tip speed had a stable value.

An approach was used in which one value of equivalent stress was determined to perform the tests. Its value is equivalent to the damage done to the blade from a cycle combination. This approach is more rational since loading the blade in ground-based benches with a large number of possible cycles, as proposed, for example, in [11], is difficult and time-consuming. The flight profiles of ultralight helicopters are very different from each other. Loading, even with a large number of cycles, will not allow the flight profiles of most ultralight helicopters to be simulated.

Table 1

Data of bending moments in the root part of the blade

Flight mode	Moment amplitude in the vertical plane	Medium moment in the vertical plane	Moment amplitude in the rotational plane	Medium moment in the rotational plane	Relative time
	M_{azi}	M_{mzi}	M_{axi}	M_{mxi}	$\overline{t_i}$
	Nm	Nm	Nm	Nm	%
Minimal take-off weight					
Hovering	16	18	50	54	22
Acceleration	26	28	62	57	1.5
Cruising speed	24	28	57	40	25
Maximal speed	29	45	75	45	1
Braking (deceleration)	27	22	75	31	0.5
Maximal take-off weight					
Hovering	22	-58	69	62	22
Acceleration	22	-24	50	59	1.5
Cruising speed	21	-27	57	42	25
Maximal speed	34	-19	78	34	1
Braking (deceleration)	22	-12	56	31	0.5

A special fatigue bench for blades was created on which tests were carried out in accordance with equivalent loads to further determine the operational time of the blade.

Fig. 1. Ultralight helicopter VA115

3. GROUND FATIGUE TEST

The composition of the blade fatigue bench is presented in Fig. 4. Two cut blades (4) and (6) were used for the tests. Longitudinal tensile force F_{cb}, which simulated centrifugal force, and transverse force F_e, which generated bending moments, were applied to them. The exciter (3) created a transverse exciting force during the bench operation. This force swung the blades. The inertial force from the concentrated mass on the technological hub (5) counteracted the exciting force. The tensile force was created by a sling system (1) and connected to blades through a dynamometer (2). The distance between the points of force application led to the appearance of a bending moment. All tests were executed at the resonant frequency of the blade kit to increase the amplitude. A photo of the bench is presented in Fig. 5.

Fig. 2. Measuring equipment on the coaxial rotor system

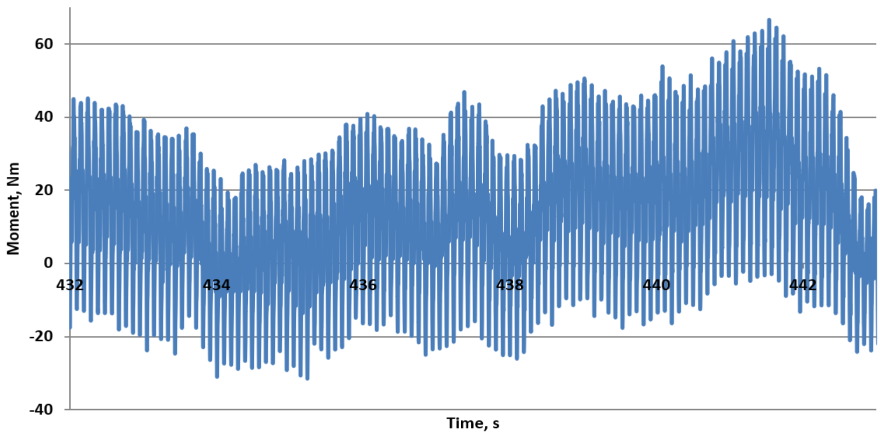

Fig. 3. Loads on the lower rotor blades during the flight with maximum speed

A counterflow arises during the bench designing: on the one hand, it is necessary to use a sling system that is as long as possible to decrease the influence of tensile force to exciter. On the other hand, a long sling system reduces the resonant frequency, which reduces the effectiveness of the bench for fatigue testing of small blades, typical for ultra-light helicopters. In this case, the 1.9 ratio of the lengths of the blade and the cable system were chosen.

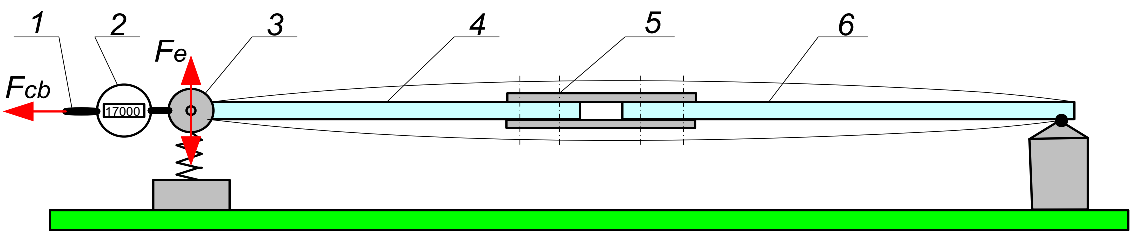

Fig. 4. Test bench composition

Six half bridges of strain gauges were glued to tested blade parts. The largest bending moment was near the connections of one blade to another and this value was used for the calculation.

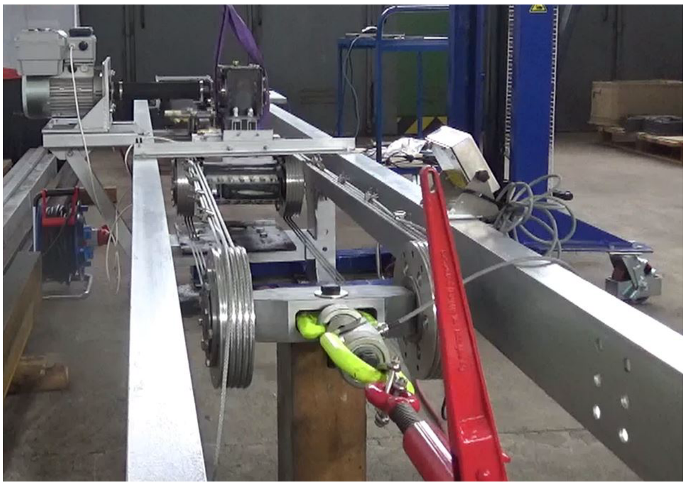

Fig. 5. Photo of the bench for blade fatigue testing

After the bench was set up, the bending moments on the test blades were determined. The first and second blades had different bending moments because they had different positions to support. In accordance with the conservative approach, it was necessary to consider a smaller value of moment for both blades. It was 45.3 Nm with a frequency of 6.5 Hz during the test. Stresses in the blades were caused by resonant deflections of the technological hub since the exciting system did not change during the tests. Figs. 6 and 7 show the bending moments in the vertical plane at the beginnings and ends of the tests.

Tests were carried out over 600 hours on the bench. The stresses on the blades were determined using strain gauge data. The calibration of strain gauges and measurement of load values on the blades was done before the tests began and again before they ended. They were calibrated by static load. A comparison of calibration data is needed because it allowed us to check whether the strain gauge was operational during all the stress tests. The performance of the strain gauge at the end of the test was assessed by the derivative of the calibrated bending moment to voltage.

During the tests, two main forces were applied to the blade compartments to assess the fatigue characteristics of the blade. The vertical force F_e created a bending moment at the root of the blades, and axial force simulated centrifugal force F_{cb}=17,000 N. A metallic sling system with a digital dynamometer for tension force simulation was used on the testing bench. The sling tension system had axial deformation during the working. Therefore, axial force was controlled all the time during the test.

The design features of equipment for ground testing were affected by the scale factor. In particular, the elements for fastening and activating vibrations were relatively heavy. Thus, the system with two small blades and an exciter had a low resonant frequency of oscillation. There are significant features that must be taken into account when designing fatigue testing benches for helicopter blades of the low-weight category. On the other hand, small helicopters have a rotor tip speed of 160–210 m/s [1], while large helicopters use values of 180–230 m/s [12]. Thus, rotor tip speeds are similar for smaller diameters. Accordingly, the rotor rotation frequency is much higher. As a result, during testing, the rotation frequency of the main rotor can be greater than the frequency of the moving part of the bench. It has a negative influence on the time testing.

4. DETERMINATION OF BLADE OPERATIONAL TIME

The blade operational time must be selected such that no blade failure occurs due to fatigue damage. Fatigue failure of a blade occurs from defects on the surface or inside the strength element of the blade. Under tension fatigue loading, damage appears through a loss of longitudinal stiffness. Damage is also introduced through stiffness decrease in spring interface elements. The initial stiffness is initially numerically infinite (sufficiently high value), and it decreases as a function of the sustained strain and the number of cycles. In actual modeling, interface elements collect longitudinal strain in neighboring quadrangle elements. This modeling thus uses a kind of communication between elements of different types [13].

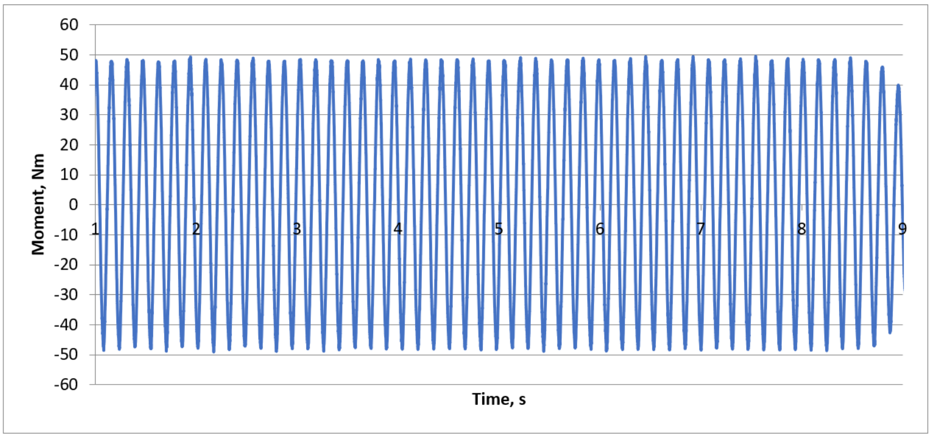

Fig. 6. Recording parameters of the root half bridge of strain gauges on the test blade at the beginning of the test

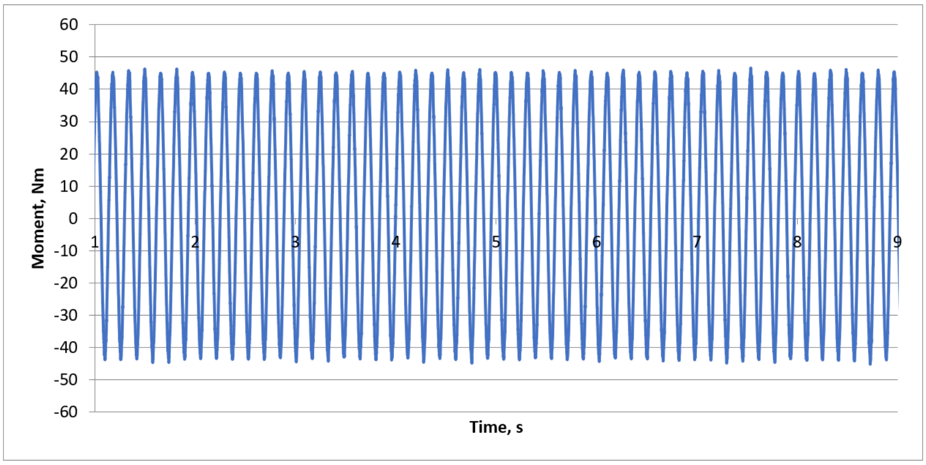

Fig. 7. Recording parameters of the root half bridge of strain gauges on the test blade at the end of the test

Durability dissipation during specimen testing is characterized by the distribution function of the number of cycles until specimen failure. For blades, such destruction obeys the normal law. The probability distribution of destruction can be described by the equation

$$P = \int_{-\infty}^{\xi} \varphi(\xi) d\xi \quad (1)$$

There is some deviation from the normal law, with a low probability of destruction, which indicates that the destruction of the blade can occur only when a minimum number of cycles is performed. Accordingly, in this case, the probability of destruction may be close to zero. The assignment of the blade operational time should also be established with a probability of destruction close to zero $P \to 0$ [11].

It is advisable to use equivalent stresses to perform calculations. The equivalent stress amplitude is a constant stress amplitude that introduces damage to the structure equal to that introduced by alternating stress amplitudes of different magnitudes in all flight modes.

Total equivalent stress depends on the equivalent amplitude and medium stresses on the vertical and horizontal planes. Medium stresses can be summarized simply as a sum of squares (2). However, such a parameter in a real blade is achievable in the lower part of the blade with an asymmetrical airfoil. This part may have a flatter shape. For a more accurate calculation, it is necessary to take into account the shape of the blade, since the value of the maximum average stress may be less, especially if the blade has a symmetrical airfoil. Stress from amplitude cannot be determined so easily. In flights, situations when the amplitudes are in phase occur rarely. The phase coincidence parameter of vertical and horizontal stresses ε is used for the evaluation of loads summarizing. It is possible to use an approach in which the probability of phase convergence of the blade oscillation amplitudes is estimated according to Equation (3).

$$\sigma_{mM} = \sqrt{\sigma_{mMz}^2 + \sigma_{mMx}^2} \tag{2}$$

$$\sigma_{aM} = \sigma_{aMz} + \varepsilon\left(\sqrt{\sigma_{aMz}^2 + \sigma_{aMx}^2} - \sigma_{aMz}\right) \tag{3}$$

In this case, the value of ε can be determined by analyzing the ratio of load records in the vertical and horizontal planes. In cases where the stress phase relationship in different modes is uncertain, it is possible to use $\varepsilon = 0.5$ [7] according to the conservative approach. The equivalent stresses from the amplitude and the medium value in both the horizontal and vertical planes can be determined quite accurately from simple load ratios in all flight modes.

$$\sigma_\Sigma = \sqrt[k]{\sum_1^n \sigma_i^k \, \overline{t_\iota}} \tag{4}$$

The equivalent stress for blade loads is determined fairly accurately at k=3.

The amplitude of the bending moments exerts the main influence on fatigue strength. Loading with a constant bending moment has little effect on the fatigue strength of the blade, especially at low stresses. The influence of this loading on the value of the cycle's amplitude can be defined through the determination of the magnitude of the increased amplitude of the moment. To do this, it is necessary to determine the ratio of the amplitude and medium limit stresses first. As is known, the greater the static load from centrifugal force, the less bending fatigue stress the sample can withstand.

The limit equivalent value of the stress amplitude at a given medium stress can be determined through the linear Goodman equation [14].

$$\sigma_{ap} = \sigma_{-1}(1 - \frac{\sigma_m}{\sigma_p}) \tag{5}$$

The limit of fatigue strength of CFRP can be considered according to [15]:

$$\sigma_{-1} = 0.40\sigma_p \tag{6}$$

The medium stress value depends on the value of the medium moment and centrifugal force:

$$\sigma_m = \sigma_{mM} + \sigma_{mT} \tag{7}$$

It was $\sigma_m = 7.3\ MPa$ in the case of the investigated VA115 helicopter.

The considered blade had many layers of composite material. The main loads of the blade were in the longitudinal direction. Therefore, the main part of the blade spar consisted of one directed CFRP fiber. Partial layers consisted of two directed fabrics with a position of ±45° to the longitudinal axis for withstanding the torsion loads. Young's modulus was too small in the longitudinal direction. The fiber volume content for longitudinal stresses was not high. It was about 30%. In accordance with [16], $\sigma_p = 1000MPa$ can be considered as a tension ultimate stress for described CFRP. The blades did not compress the zone. The value of the limit equivalent amplitude of the moment also will be different for compression and tension, but the rotor blade had such a large centrifugal force that the appearance of a compressed zone was not possible. For considered helicopter, it was $\sigma_{ap} = 397.8\ MPa$ for tension area.

Thus, a medium value ratio of Haigh diagram stresses is

$$\bar{\sigma}_{\mathrm{a}} = \frac{\sigma_m}{\sigma_{ap}} \tag{8}$$

According to the conservative approach, the maximal value for considered rotorcraft was $\bar{\sigma}_{\mathrm{a}} = 0.013$.

Increasing stress amplitude from the medium moment can be defined by the next relation [7]:

$$\Delta\sigma_a = \bar{\sigma}_{\mathrm{a}} \cdot \sigma_{\mathrm{m}} \tag{9}$$

Total equivalent stress:

$$\sigma_\Sigma = \sigma_{aM} + \Delta\sigma_a \tag{10}$$

The minimum number of blade cycles on the bench corresponding to the damage of the blade in flight can be determined from Wöhler dependence:

$$N_{min} = \left(\frac{\sigma_\Sigma}{\sigma_t}\right)^m N_h \tag{11}$$

Generally, $m = 6$ in Equation (12) is used for metal parts fatigue investigations. Usually, this is too small for composite material but when the fatigue parameters of the composite material combination are unknown, this degree can be used according to the conservative approach.

It is almost impossible to define a Wöhler curve for the blade itself when assessing the fatigue strength of a blade since, in this case, it would be necessary to perform experiments on a large number of examples because this would require a large number of blades, time for testing them, and equipment for measurements. Typically, a small number of samples is used to test blades. In some cases, a simplified procedure is used for low-weight manned and unmanned helicopters. In this case, small pieces of real blades are used to define the Wöhler curve. Since the procedure for determining the blade life is necessary not only for the tasks of analyzing the strength of a helicopter but also for admission to flights and certification, the choice of approach depends on the certification authorities of the country that issues the flight permit.

Operational time assignment should be carried out by the number of cycles of guaranteed safe deformations:

$$N_s = N_{min}\eta_f\eta_N \tag{12}$$

Frequency safety factor η_f due to an increase in the temperature of the test blade at an increased frequency of oscillations on the bench [7, 17]. The self-heating effect is an unfavorable phenomenon that occurs in polymer structures subjected to vibrations or fatigue loading. The intensity of the self-heating phenomenon in such structures can be a function of material properties, geometry, and loading conditions. When a blade specimen is subjected to a cyclic mechanical loading, such CFRP due to its viscoelastic nature tends to dissipate a portion of mechanical energy in the form of thermal energy. The rest of the energy is dissipated due to elastoplastic behavior and fracture mechanisms, which occur from the very beginning of the operation. Due to the generally low thermal conductivity of polymers, this thermal energy is stored in a structure. Since the stored thermal energy is accumulated, it provokes the heating of a structure and consequently the decrease in its mechanical performance, causing irreversible changes in a material at the final stages of degradation. Structural changes in a material influenced by self-heating are caused by an increase in the activity of polymer chains with the increase in temperature, which results in CFRP softening and, in extreme cases, in the breaking of polymer chains. This can be considered a source of irreversible structural changes at the macroscopic level. This phenomenon is manifested by mechanical hysteresis when a structure is under cyclic loading. The influence of this phenomenon can be defined via the frequency safety factor according to Table 2.

The approximation of the data in Table 2 can be presented according to the following equation:

$$\eta_f = -0{,}0028\left(\frac{f_t}{f_h}\right)^2 + 0{,}1417\frac{f_t}{f_h} + 0{,}8611 \tag{13}$$

The current test with a small blade was done with low frequency. Therefore, this influence was not considered in the calculation of the VA115 blade $\eta_f = 1$.

Table 2

Frequency safety factor

$\frac{f_t}{f_h}$	η_f
1	1
5	1.5
10	2

Safety factor by number of cycles η_N shows the necessary increase in the number of cycles for small amounts of test samples. Dispersion in the parameters of blade samples may occur during testing, even for blades manufactured under similar conditions. The spread in the fatigue strength characteristics of a composite blade is explained by the heterogeneity of the material structure and differences in the technological process. Safety factor by number of cycles is defined according to Table 3 [7]. Two blades were tested simultaneously on the bench; thus, $\eta_N = 8$. This means that the ground test time needs to be increased by eight times if only two blades are in operation.

Table 3

Safety factor by number of cycles

Quantity of tested blades	η_N
1	12
2	8
3	6
6	4

The number of cycles of guaranteed safe deformations can be changed to the next view.

$$N_s = \frac{N_h \eta_f \eta_N}{{\eta_\sigma}^6} \tag{14}$$

The loading of test samples was carried out by an increased bending moment of the test. The load ratio was determined by the stress safety factor η_σ.

$$\eta_\sigma = \frac{\sigma_t}{\sigma_\Sigma} \tag{15}$$

The bench frequency was small, and there was a possibility of reducing the test time by increasing stress during the ground test. For the VA115 blade, the stress safety factor was $\eta_\sigma = 1.8$. Of course, such a load increase does not exceed the limit value for the material and contact pair, but at the same time, it is significant. A smaller increase in loads (e.g., $\eta_\sigma = 1.2$) would improve the accuracy of the blade life simulation, but for small helicopters, this would lead to a significant increase in ground testing time. The solution in this case is to use the additional reserve from the calculated operational time.

Time of bench working in hours:

$$T_t = \frac{N_s}{f_t \cdot 3600} \tag{16}$$

Assigned blade resources according to the test results of the blade on the bench:

$$R_h = \frac{N_h}{f_h \cdot 3600} \tag{17}$$

The number of loading cycles of a helicopter blade corresponds to a given operational time.

$$N_h = f_h \cdot 3600 \cdot R_h \tag{18}$$

In particular, this amount was $39 \cdot 10^6$ cycles for 1000 flight hours for the VA115 helicopter. After the number of cycles required for guaranteed safe deformations was determined, the operating time of the blade in flight was determined. Operational flight time of 1000 hours helicopter blades is coincident to $\mathrm{T_t} = 290$ hours on the bench.

5. CONCLUSIONS

The described method for determining a blade makes it possible to easily determine a low-weight helicopter blade's operational time using the presented example of a VA115 helicopter. As a rule, other approaches were used for small-weight helicopters instead of for helicopters of a medium and large category. On ultralight vehicles, the operational time was usually determined using small samples of blade material or by recalculating the limit static load. This method may not always give accurate results. In this case, it is recommended to use a bench with simultaneous testing of two blades. The advantages of such a bench were a 1.5-fold reduction in testing time and a reduction in loads in the activating part of the bench. The 1.9 ratio of the lengths of the blade and the cable system was chosen for the bench. However, the experiment revealed a negative influence of the scale factor. The resonant bench may have a low frequency, even though the angular speeds of small helicopter rotors are quite significant. The relationship between resonant frequency and helicopter rotor RPM causes a significant increase in the effective stresses of the blades during ground tests. The proposed method for recalculating experimental data, based on existing research results, makes it possible to determine the fatigue parameters of the blade based on the results of operating time on the bench.

In particular, for the VA115 helicopter, it was determined that 290 hours at the specified bending moments will correspond to the safe required operational time of the blade 1000 hours in flight. Ground tests conducted over 600 h allowed us to guarantee the required operational time.

The proposed method and experimental results can be useful to specialists engaged in research in the field of one- to two-seat manned helicopters of a small weight category and unmanned. In recent years, relations towards these areas of transport have changed significantly. A large number of safety requirements have appeared. The proposed approach can allow manufacturers to guarantee the safety of vehicles in the rotor.

Further research should take into account the influence of the scale factor at the bench. In particular, it is necessary to increase the operating frequency of the bench as much as possible. In addition, it is necessary to study the stress distribution of the root part of the blade on the bench. Also, research should study blade fatigue in cases of possible damage to the blade from small stones and hale.

Nomenclature

F_{cb}	axial force for centrifugal force simulation	N
F_e	vertical force for bending moment simulation	N
f_h	rotation frequency of the main rotor	Hz
f_t	frequency of the blade deformation on the bench	Hz
i	number of flight mode	
k	degree parameter of blade stress summarising	
m	degree parameter of the Wöhler equation	
N_{min}	minimum number of blade cycles on the bench corresponding to the blade in flight	
N_h	number of vibrational cycles of the blade corresponding to the established operational time	
N_s	number of cycles of guaranteed safe deformations	
n	number of flight modes in which the tests were carried out	

P	distribution probability of the blade destruction	
R_h	approved blade operational time according to the test results of the blade on the bench	
T_t	time of bench test	h
$\bar{t}_i$	relative time of flight on the specific mode	%
ε	parameter of phase coincidence of vertical and horizontal stresses	
ξ	value of the logarithm of the number of cycles before structural failure	
$\Delta\sigma_a$	conditional increase in stress amplitude due to average load	MPa
η_σ	stress safety factor	
η_f	frequency safety factor	
η_N	safety factor by number of cycles	
$\varphi(\xi)$	density probability distribution of structure failure	
σ_i	stress in the flight mode in the horizontal or vertical plane	MPa
σ_{ap}	limit equivalent value of stress amplitude	MPa
$\bar{\sigma}_a$	the relative value of the medium stress to the amplitude stress	
σ_{-1}	limit of fatigue strength of the material	MPa
σ_p	limit of static strength of the material	MPa
σ_m	medium value of stress	MPa
σ_{aM}	equivalent amplitude stress in the blade from the bending moment	MPa
σ_{aMx}	equivalent amplitude stress in the blade from the bending moment in the horizontal plane	MPa
σ_{aMz}	equivalent amplitude stress in the blade from the bending moment in the vertical plane	MPa
σ_{mM}	equivalent medium stress in the blade from the bending moment	MPa
σ_{mMx}	equivalent medium stress in the blade from the bending moment in the horizontal plane	MPa
σ_{mMz}	equivalent medium stress in the blade from the bending moment in the vertical plane	MPa
σ_{mT}	stress in the blade from centrifugal force	MPa
σ_t	amplitude of stress in the blade during the bench test	MPa
σ_Σ	amplitude of stress in the blade from total equivalent bending moments during the flights	MPa

References

1. Dudnik, V. & Karabut, V. Ultralight and very light helicopter rotor data. *Transactions on Aerospace Research*. 2023. Vol. 271(2). P. 17-24.
2. LTF–ULH. *Bekanntmachung von Lufttüchtigkeitsforderungen für Ultraleichthubschrauber.* Braunschweig: Deutsche Flugsicherung. [In German: *Announcement of airworthiness requirements for ultralight helicopters*. Braunschweig: German Air Traffic Control]. 2019. 61 p. Available at: https://www.dulv.de/sites/default/files/Downloads/ltf%20ul-hubschrauber%202019-02-28%20nfl%202-460-19.pdf.
3. Rasuo, B. Experimental Techniques for Evaluation of Fatigue Characteristics of Laminated Constructions from Composite Materials: Full-Scale Testing of the Helicopter Rotor Blades. *Journal of Testing and Evaluation.* 2011. Vol. 39. No. 2. P. 237-242.
4. Kee1, Y. & Kim1, S. & Han, J. & Jung, J. Resonant fatigue testing of full-scale composite helicopter rotor blades. In: *15th European Conference on Composite Materials.* Venice. Italy. 2012. Available at: http://www.escm.eu.org/eccm15/data/assets/2474.pdf.
5. Zheng, J. A flight load test method for helicopter rotor blade. *International Journal of Mechanical Engineering and Applications.* 2021. Vol. 9. No. 5. P. 75-78.

6. Cooke, A. & Fitzpatrick, E. *Helicopter test and evaluation.* Oxford: Blackwell publishing. 2002. 370 p.
7. Mil, M. *Helicopters. Calculation and design. Volume II. Vibration and Dynamic Stability.* Washington: National Aeronautic and Space Administration. 1968. 470 p. Available at: https://apps.dtic.mil/sti/pdfs/AD0683091.pdf.
8. Feil, R. & Rinker, M. & Hajek, M. Flight testing of a coaxial ultralight rotorcraft. In: *73 Annual Forum of American Helicopter Society*. Paper 89. Fort Worth, 2017. Available at: https://www.researchgate.net/publication/319618214_Flight_Testing_of_a_Coaxial_Ultralight_Rotorcraft.
9. Rapp, C. & Wedemeyer, P. Measurement of in-flight rotor blade loads of an AutoGyro. In: *26 European Rotorcraft Forum*. Hague. 2000. Available at: https://dspace-erf.nlr.nl/items/a6ef96c4-b131-4fdd-95ee-6dfb7d6ad90e.
10. Dudnik, V. Determination of loads in the ultralight helicopter blades. *Aviation*. 2023. Vol. 27. No. 4. P. 242-247.
11. Kee, Y. & Kim, S. & Han, J. & Jung, J. & Hur, J. High cycle fatigue life evaluation of damaged composite rotor blades. *Transactions of the Korean Society of Mechanical Engineers A.* 2012. Vol. 36. P. 1275-1282.
12. Rand, O. & Khromov, V. Helicopter sizing by statistics. In: *58 Annual Forum of American Helicopter Society*. Montreal, 2002.
13. Rouault, T. & Nègre, V. & Bouvet, P. & Rauch, C. Study of the crack growth in composite rotor blade skin. In: *38 European Rotorcraft Forum.* Amsterdam. 2012. Available at: https://dspace-erf.nlr.nl/items/399b5eca-bfcc-4c13-9318-94190a31b948.
14. Jelaska, D. On the Goodman's fatigue safety factor. *International Journal of Advanced Engineering*. 2011. Vol. 5. P. 27-34. Available at: https://www.researchgate.net/publication/269695668_On_the_Goodman's_Fatigue_Safety_Factor.
15. Стрижиус, В. *Методы оценки усталостной прочности элементов композитных авиаконструкций*. Москва: Машиностроение. 2015. 270 p. [In Russian: Strizhius, V. *Methods for Assessing the Fatigue Strength of Composite Aircraft Structures,* Moscow, Mashinostroenie].
16. Brunbauer, J. & Stadler, H. & Pinter, G. Mechanical properties, fatigue damage and microstructure of carbon/epoxy laminates depending on fibre volume content. *International Journal of Fatigue.* 2015. Vol. 70. P. 85-92. Available at: https://www.sciencedirect.com/science/article/pii/S0142112314002126.
17. Amraei, J. & Katunin, A. Recent advances in limiting fatigue damage accumulation induced by self-heating in polymer–matrix composites. *Polymers.* 2022. Vol. 14(24). No. 5384.

Received 07.04.2023; accepted in revised form 03.09.2024