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THE METHODOLOGY OF FATIGUE LIFETIME PREDICTION AND VALIDATION BASED ON ACCELERATED RELIABILITY TESTING OF THE ROTOR PITCH LINKS

METODOLOGIA PROGNOZOWANIA TRWAŁOŚCI ZMĘCZENIOWEJ ORAZ JEJ WALIDACJA W OPARCIU O PRZYSPIESZONE BADANIA NIEZAWODNOŚCI DŹWIGNI SKOKU WIRNIKA NOŚNEGO

Because the industrial products have lifetimes, without failing, of up to millions of cycles, it is mandatory that the aerospace field puts into practice the accelerated testing techniques. The lifetime prediction methodology for industrial products presented in this paper was put into practice by performing accelerated reliability testing on an aerospace product (the pitch link of a helicopter). The results showed a significant reduction of the testing time and costs. One important aspect highlighted in this paper is the equivalence between accelerated reliability testing and the traditional reliability testing, by using the two fundamental principles of the accelerated experiments: first, the stresses applied must not alter the physical mechanism through which the defects are produced and second, the conservation of the distribution laws of the failure times. In this way, by equivalence of the accelerated experiments, the methodology contained in this paper was validated.

Keywords: *reliability, validation, fatigue life, accelerated reliability testing, pitch links.*

Ponieważ okresy bezawaryjnego użytkowania produktów przemysłowych stosowanych w w branży lotniczej mogą wynosić nawet kilka milionów cykli, badanie niezawodności tych wyrobów wymaga zastosowania technik badania przyspieszonego. Metodologię prognozowania czasu pracy produktów przemysłowych przedstawioną w niniejszym artykule wykorzystano w badaniach przyspieszonych niezawodności dźwigni skoku wirnika nośnego helikoptera. Wyniki wykazały, że proponowana metoda pozwala na znaczną redukcję czasu i kosztów badania. Ważnym aspektem, podkreślonym w niniejszej pracy, jest równoważność przyspieszonych i tradycyjnych badań niezawodności, którą można uzyskać respektując dwie podstawowe zasady eksperymentów przyspieszonych: po pierwsze, zastosowane naprężenia nie mogą zmieniać fizycznego mechanizmu, który prowadzi do powstania wady, a po drugie, należy przestrzegać praw dotyczących rozkładu czasów uszkodzeń. Przeprowadzone badania potwierdzają poprawność proponowanej metody.

Słowa kluczowe: *niezawodność, walidacja, trwałość zmęczeniowa, przyspieszone testy niezawodności, dźwignia skoku.*

1. Introduction

The growing global competition determined the producers to develop products having multiple characteristics with high reliability, at a reduced cost and in the shortest time possible. The challenges posed by these objectives pushed forward the manufacturers to develop and use efficient reliability methods that include accelerated reliability testing. Accelerated experiments are an economic way of getting faster the information regarding the behavior of the products.

The acceleration of the conditions, meaning the "time testing compression" can be studied relative to the number of cycles until failure. To reduce the testing time the stress is applied over the normal limits, keeping the mechanism of failure [9].

The accelerated reliability testing imposes limits like [6,7]:

- the nature of the defects for the accelerated levels has to be the same;
- the test specimens subjected to accelerated testing have to be similar to those used for normal stress;
- the adjustment of the testing model has to be in accordance with the tested product's working parameters;
- every sampling tested at a certain stress needs to be statistically homogenous;
- the results of the accelerated testing must not be extrapolated outside the boundaries of the acceleration model.
- the acceleration model between stress and life time has to conform structurally and functionally to the tested product.
- the accelerated levels must not modify the way the product fails in normal conditions (the distribution of the operating time is not modified, meaning that the shape of the probability density is not changed).

The accelerated reliability tests are developed in a great variety. Each company has the freedom to choose the applied loads for its products because these are considered internal tests, the client receiving only the equivalent results (reliability indicators) determined by extrapolating them from the accelerated level to the normal use one [11]. The research regarding the failures of the aerospace structures highlight the necessity to complement and implement modern computational methods for testing them, both in static and dynamic level.

The fatigue tests have decisive influence over the reliability of aerospace structures so that the statistical characteristic of the fatigue calculation for this kind of stress has to be taken into consideration, including the statistical nature of the stress itself. If an aerospace structure requires for example 10^6-10^7 cycles to produce a fatigue failure in normal testing conditions, by using of accelerated testing the same result can be obtained after 10^4-10^5 cycles [14,16, 18].

In the case study (the helicopter pitch link) presented in this paper there a cyclical mechanical stress was applied. For cyclical stresses the mechanical systems and components are most often used and the most often met failing phenomenon is the fatigue. The fatigue testing for different components (helicopter blade [20], supple platinum [21], pitch links [17,23], wing spar [3,13] and landing gear [1,12]) can have millions of cycles until failure. For this reason the use of accelerated testing is a method through which the time testing for aerospace components is shortened and thus the testing system is made more efficient [5, 8, 10, 22]. The scope of the present study is the investigation of fatigue life prediction of pitch links components from the IAR 330 helicopter structure subjected to accelerated reliability testing.

2. Experimental details

In fig. 1 is presented: the anti-torque rotor hub contains a body (2) and five assemblies spindle-sleeve (3) that allows: blade feathering; blade pitch change through the swash plate (1) and the pitch link (4) to the swash plate – pitch lever (5).

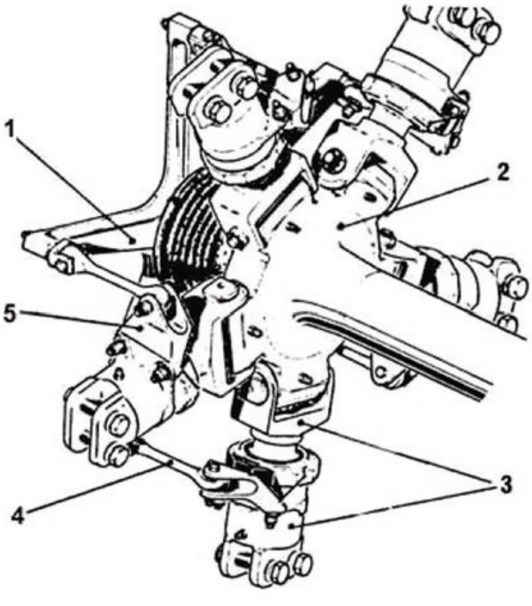


Fig. 1. Rotor hub assembly [4]

The pitch link (fig. 2) is a vital element found in the helicopter made from aluminium alloy. The pitch variations for the tail rotor blades are transmitted with the help of a servo drive. The servo drive acts on the drive plate connected at the blade sleeves through the pitch links with the help of a mast.

The tension testing device (fig. 3) for the pitch links contains the following components:

- the pitch links' fastening device (3) that allows to fasten the pitch link (2) similar with the fastening on the helicopter;
- the pitch links tensioning device (1) with the help of an electric engine (4) through trapezoidal belts drives the cam mechanism, which at its turn through the kinematic chain determines an alternating movement of 2-5 cm for the links;
- with the help of an elastic element this alternating movement generates a dynamic force in the tested link;

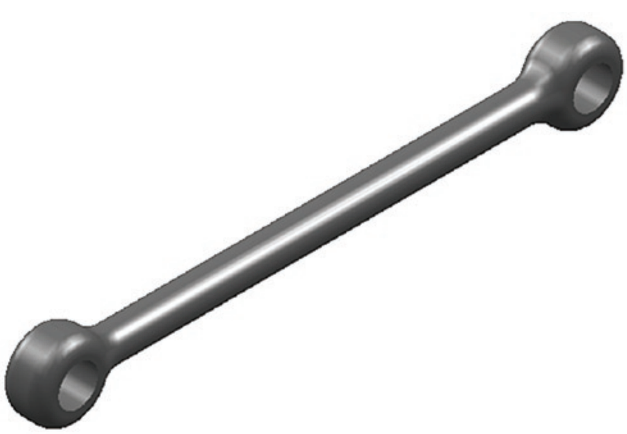


Fig. 2. Pitch link

- a cycle counter (5) indicates the number of cycles of fatigue testing of the pitch link;
- the control and automation (6) installation represents a part of the experimental stand that has the role of starting the electric engine and to stop the stand when a fissure appears, by decoupling the force and the engine.

3. The acceleration function method

The equivalence between the accelerated and normal testing requires that the following conditions are met [2]:

- the applied stress must not alter the physical mechanism for producing the faults: within the accelerated testing there must not be any other fault types or new faults related to the deteriorations, the only difference being the increase for of the occurrence of the fault.
- the conservation laws for the failing time distributions: the distribution functions have to remain the same for different defects, with the condition of increased speed in the appearance of the faults.

The first principle represents the basis for adopting the level of the applied overload, and the second principle certifies that the level of the overload does not exceed the allowable loading. The statistical analysis of the accelerated reliability testing is done in relation to the

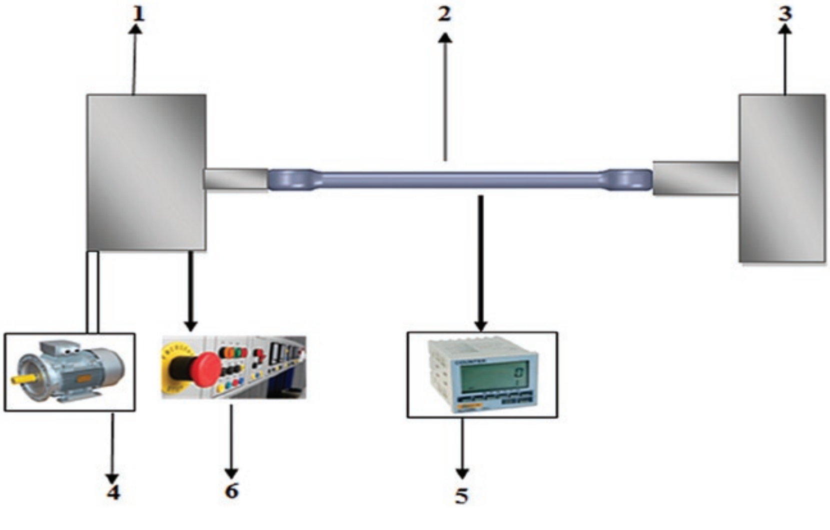


Fig. 3. Testing bench for the rotor pitch links

known rated normal level (from the producer's testing data sheet). The interpretation of the accelerated testing results is done in relation to the normal ones in known (standardized) normal conditions. It is necessary to know the rated stress reliability characteristic.

In this paper the accelerated testing will be validated by modelling the distribution laws (Weibull) of the failure times and the related parameters. When the modelling refers to the distribution law of the failing times, like the Weibull distribution, it is mandatory the values of the ß shape parameter from the normal testing (from the product data sheet) and from the accelerated testing are close, although the (η) scale parameter varies.

The most important aspect regarding these types of accelerated reliability tests is the equivalence between these and the normal level testing. The equivalence relationship can be obtained on the basis of equal reliability postulate which represents the theoretical foundation for accelerated testing. If for all the positive values of t the Rsn(t) > Rsa(t) is true then sn>sa. The equal reliability postulate shows the fact that for two stress levels (sn – normal and sa – accelerated) exists the equality of the reliability functions, as shown in the expression:

$$Rs_n(t) = Rs_a(\omega). \tag{1}$$

This equation (2) has a graphical correspondence in fig. 4 and implies a relationship between the moments (t, ω) through an acceleration function:

$$t = a(\omega). \tag{2}$$

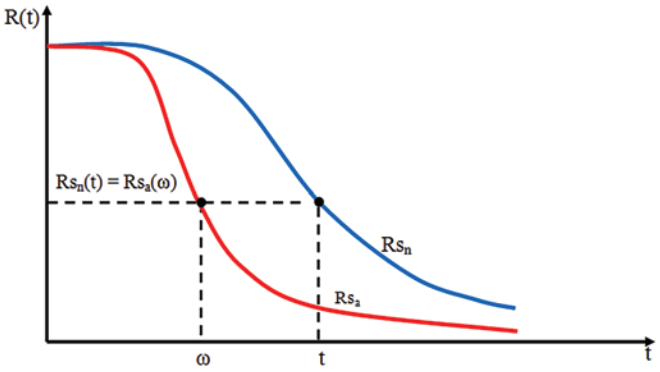


Fig. 4. Acceleration function

In the accelerated testing conditions, the accelerating function a(t) is a monotonically increasing function having the following properties:

$$\begin{cases} a(0) = 0 \\ \lim\limits_{\omega \to \infty} a(\omega) \to \infty \end{cases}. \tag{3}$$

The function a(ω) can be analytically expressed if the random variable's distribution law is known. In the case of the two parameter Weibull distribution we obtain the relationships:

$$Rs_n(t) = e^{-\left(\frac{t}{\eta_0}\right)^{\beta_0}}. \tag{4}$$

$$Rs_a(\omega) = e^{-\left(\frac{\omega}{\eta}\right)^{\beta}}. \tag{5}$$

From the equations (1), (4) and (5) we obtain the acceleration function relationship for the two parameter Weibull distribution:

$$t = \frac{\eta_0}{\eta^{\left(\frac{\beta}{\beta_0}\right)}} \cdot \omega^{\left(\frac{\beta}{\beta_0}\right)} = F \cdot \omega^n = a(\omega). \tag{6}$$

where the parameters F and n are constant (for given testing conditions) and can be experimentally determined. In this way, starting from the expression (6) the values for the variable parameters and for the normal loading distribution indicators can be obtained, if the values for the accelerated stresses are known.

4. Statistical analysis of accelerated reliability results

After the preceding steps of the accelerated reliability tests have been performed, the following statistical processing algorithm for the accelerated testing data was adopted, as represented in fig. 5.

This statistical data processing algorithm starts with the experimental data acquisition and finishes with determining the reliability indicators for the normal testing level. The results from the pitch link testing for the 3 accelerated testing levels are shown in Table 1.

Following the statistical analysis of the experimental data, for the three stress levels the most relevant distribution was the parameter Weibull distribution. In fig. 6 are represented the probability density functions for the three accelerated levels. To test the hypothesis which states that the distribution law for the number of cycles is Weibull type, one of the testing and certifying tests of the statistical hypothesis can be used. For the statistical data's distribution check obtained from the accelerated reliability testing, the Anderson-Darling test is used. This test compares the empirical cumulative distribution function of the sample data with the distribution expected if the data were normal. If the observed difference is adequately large, the null hypothesis of population normality will be rejected.

The most adequate acceleration model for data obtained from acceleration tests where the failure mode is through fatigue is the Inverse Power Law (IPL) – Weibull model [19]. In order to determine the number of cycles until failure and the reliability indicators for the

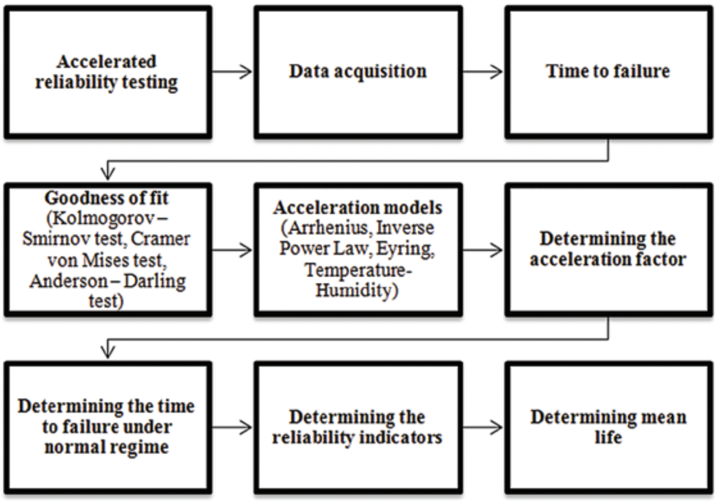


Fig. 5. The statistical processing algorithm for experimental data from accelerated reliability testing

Table 1. Accelerated reliability testing results of the rotor pitch links

No.	The number of cycles to failure in accelerated conditions	Tensile force [kN]
1	321518	17
2	384320	17
3	415470	17
4	423218	17
5	453514	17
6	214012	20
7	256080	20
8	276980	20
9	282012	20
10	302076	20
11	71437	22
12	85490	22
13	92327	22
14	94164	22
15	100891	22

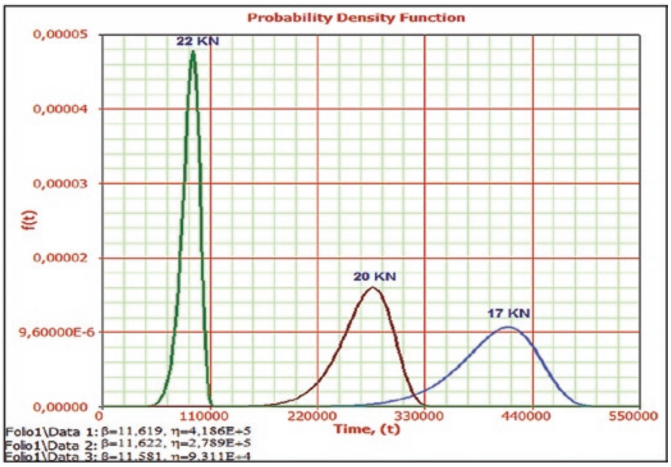


Fig. 6. Probability density plots

normal testing level (14 kN) for the pitch links, the data retrieved from the accelerated conditions were processed with the Weibull and ALTA 9 software. The three parameters characteristic to IPL-Weibull model are calculated by the maximum likelihood estimation method for the accelerated data, obtaining the following values: β=3.73; k=2.18E-12; n=4.86. The acceleration factor for the pitch links using the IPL-Weibull model has the following graphical representation (fig. 7). The acceleration factor is a number that describes a product's life at an accelerated stress level compared to the life at the normal stress level. The acceleration factor for tensile force of 22 KN is approximately 9.

As it can be seen in Table 2, the acceleration factor and standard deviation depend on the acceleration model relationship and are thus a function of tensile force.

The reliability indicators in normal conditions (F=15 kN) for the pitch links are determined using equations specific to the IPL – Weibull model according to the number of cycles until failure. In the fig. 8 there is a 3D representation of the reliability – time – tensile stresses. The reliability function represents an essential quantitative measure of reliability and has an important practical utility in the study of accelerated reliability tests. The reliability values depending on the number of cycles to failure and on the stress level in normal testing (15 KN).

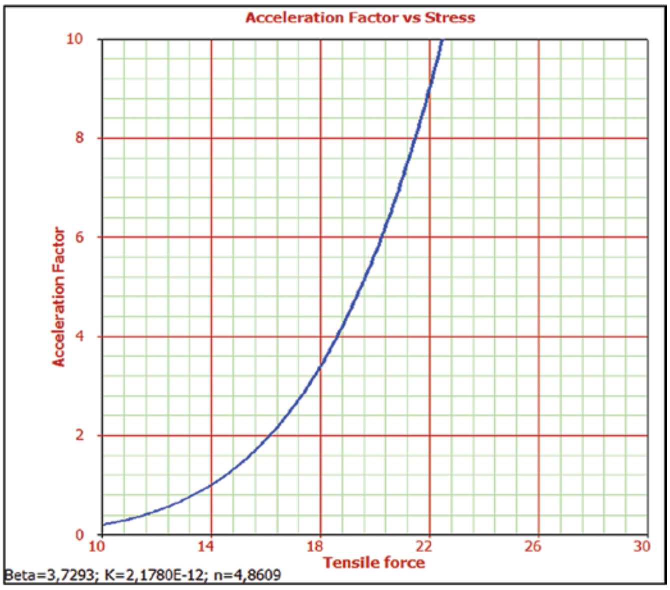


Fig. 7. The variation of the acceleration factor in relation to the tensile force

Table 2. The acceleration factor and standard deviation values in relation to the tensile force

Tensile Force [kN]	Acceleration factor	Standard deviation
14	1	332521
15	1.398	237777
16	1.914	173750
17	2.570	129402
18	3.393	98011
19	4.412	75359
20	5.662	58729
21	7.177	46329
22	8.998	36953

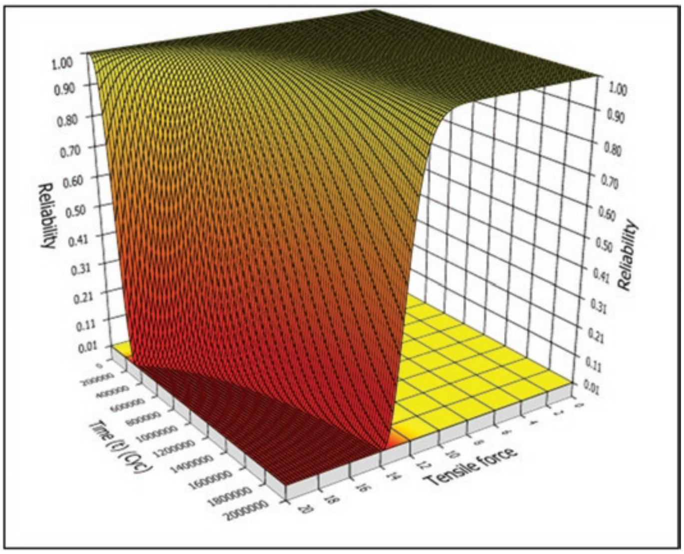
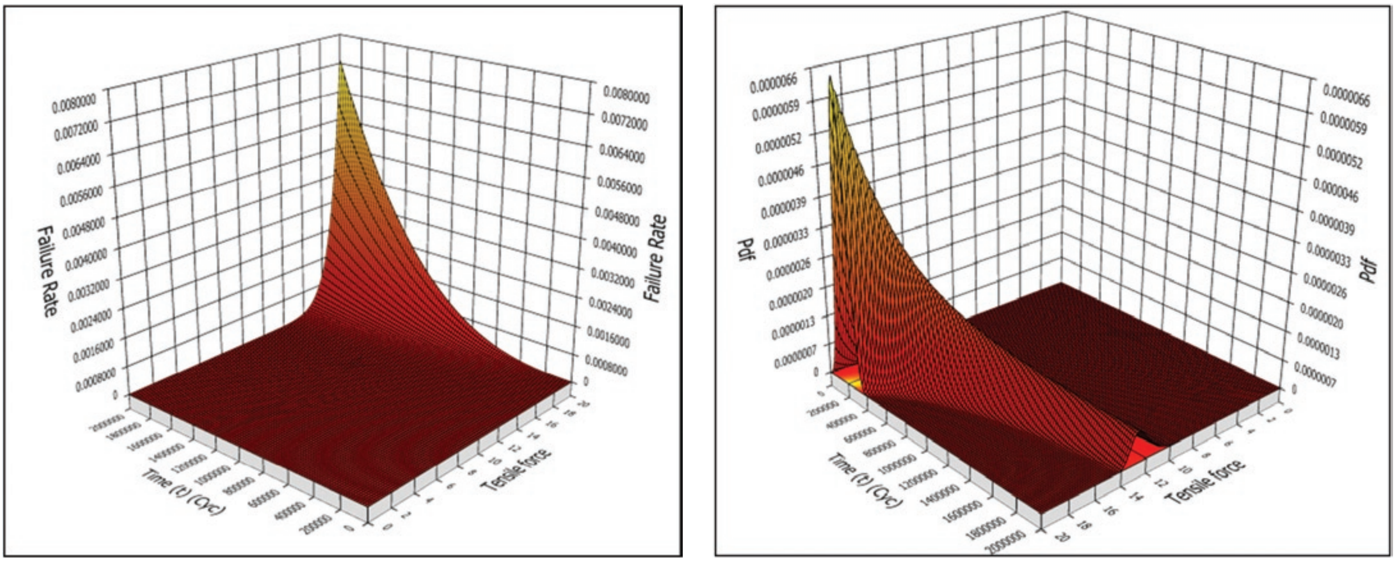


Fig. 8. Reliability function

Table 3. The dependence of the reliability indicators as function of the number of cycles to failure in normal conditions

The number of cycles to failure in normal conditions	Reliability R(t)	Unreliability F(t)	Probability density function f(t)·10^{-6}
642824	0.954	0.046	0.469
769280	0.890	0.110	0.704
826192	0.825	0.175	0.811
830803	0.760	0.240	0.820
847333	0.695	0.305	0.850
907866	0.630	0.370	0.954
987571	0.565	0.435	1.067
1067616	0.500	0.500	1.139
1087526	0.434	0.566	1.149
1165376	0.369	0.631	1.154
1211718	0.304	0.696	1.130
1449903	0.239	0.761	0.754
1568237	0.174	0.826	0.501
1596728	0.109	0.891	0.443
1710329	0.045	0.955	0.248



a) Failure rate *b) Probability density function*

Fig. 9. Reliability indicators

In fig. 9.a. is represented in 3D the failure rate – time – tensile stress. Probability density function 3D plot is represented in fig.9.b. for the pitch links.

The values for the main reliability indicators (reliability function, unreliability function and probability density function) are described in Table 3.

The fatigue life assessment for the helicopter pitch links represents one of the main objectives of this paper. In order to determine the life characteristic specific to the Weibull distribution, the graphical method is used. The mean number of cycles in normal conditions estimate the time at which 63.2% of the tested control rods are expected to fail for the three accelerated levels (17, 20 și 22 KN). At the intersection of the Eta curve, which estimates the mean (63.2%), with the axis from the normal stress level of 14 KN, finds itself the mean number of cycles to failure in normal conditions of the pitch links, which is 1232306 (fig. 10).

4. Validation of the accelerated reliability tests

The validation of the pitch links' accelerated reliability testing will be done as follows [15]:

- statistically it is done through the equivalence between the accelerated reliability testing and the normal testing conditions for the pitch links using graphically the reliability functions;
- also to certify the tests, it is mandatory that the values for the ß parameter in normal testing conditions and in the accelerated testing level are close.

The number of cycles until failure determined using the accelerated testing will be graphically represented, as well as the number of cycles until failure provided by the pitch links manufacturer in the normal testing conditions. As it can be seen from fig. 11 the β shape parameter for the number of cycles until failure determined using the accelerated testing has a value of 4.0523 and the corresponding pa-

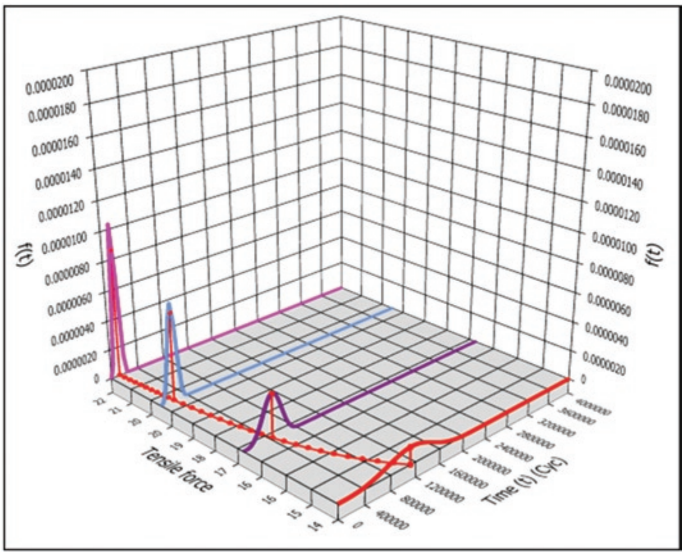


Fig. 10. Determining the mean number of cycles to failure of the pitch links in normal conditions

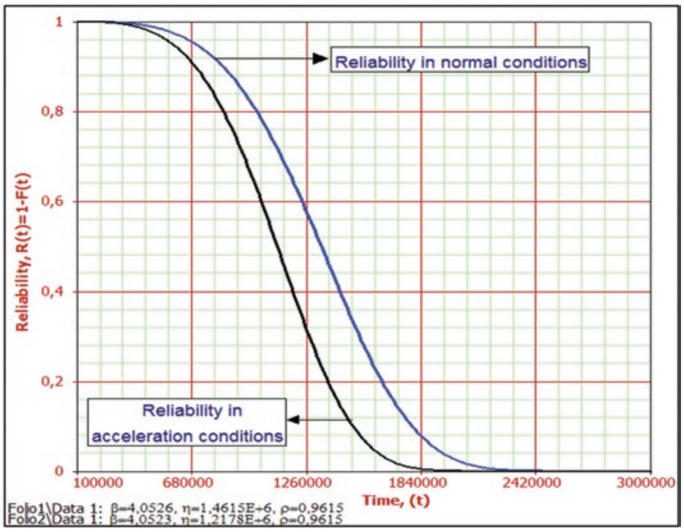


Fig. 11. The plot of reliability functions – validation of the accelerated reliability testing

rameter for the number of cycles until failure provided by the pitch links manufacturer has a value of 4.0526.

5. Conclusion

Usually, the analysis of the behavior of aerospace components during (normal) use is made based of their lifetimes, obtained by following their functioning in normal operation conditions. But in many situations, the determining of the life time of aerospace components in a reasonable timeframe is difficult or even impossible to accomplish, due to various reasons, such as: the very long life time of the products with high reliability, which in some cases can be in the order of years; the very short period of time between the design and the launch into fabrication; the continuous change of testing conditions where normal functioning regimes are used.

The main challenge that emerges by the reliability tests is their time span. To eliminate this shortcoming the accelerated reliability testing techniques are being implemented. Because the helicopter components are exposed simultaneously to various stresses in order to reduce the testing time there will be an amplification of those stresses that can determine the failure of the elements without modifying the degradation process.

In this paper, the validation of the accelerated tests was done by using the two principles: the physical mechanism of failure must not change and the conservation of failure time distribution law. By comparing the number of cycles in normal testing conditions (provided by the manufacturer) and the number of cycles that resulted from the accelerated testing, one can conclude that by using the accelerated reliability testing for the pitch links of the helicopter the number of cycles until failure was reduced by 4.5 times, a result that carries with it a major material cost reduction.

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