Evaluation of The Durability of The Design of The Nanosatellite Polytan-2-Sau on The Launch Phase

Prof . Dr. Tsybenko A.S.
The National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Ukraine
as-ts@ukr.net
Prof. Rassamakin B. M.
The National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Ukraine
bmrass@gmail.com
Rybalka A.A
The National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Ukraine
alexrybalka2408@gmail.com
N.S. Shokruta
The National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Ukraine
shokruta_ms@ukr.net

Abstract - The creation of new spacecraft requires the solution of a number of complex tasks related to ensuring the strength and durability at all stages of the life cycle of this apparatus. From the point of view of operating loads, the most difficult is the stage of launching into orbit. To ensure durability, the main interest is stationary random vibrations, they can lead to accumulation of fatigue damages and destruction of the nanosatellite design. In this paper, the determination of the durability of the design of the nanosatellite POLYITAN-2-SAU by calculation is presented. It is established that for this version of the nanotube POLYITAN-2-SAU, the condition for ensuring durability is fulfilled, which was confirmed by the successful removal of the spacecraft.

Keywords - durability, nanosatellite, stationary random vibration, strenght

Introduction

Nanosatellite (NS) PolyITAN-2-SAU was developed at the National Technical University of Ukraine " Igor Sikorsky Kyiv Polytechnic Institute" in the framework of the international space project QB50 under the overall coordination of the Institute of Hydrodynamics von Karman (Belgium). The main task of the QB50 project is to study the Earth's climate change. At present, the NS PolyITAN-2-SAU had launched into the near-Earth orbit is part of the scientific space network intended for studying the thermosphere. The NS carries a payload on board - an experimental sensor for analyzing the oncoming gas flow FIPEX, capable of distinguishing and measuring the characteristics of atomic and molecular oxygen, which is the main element at altitudes of 90-420 km from the earth's surface. The data obtained are used to evaluate models of the thermosphere.

PolyITAN-2-SAU is made according to the non-hermetic scheme in the standard CubeSat. The CubeSat program was launched at Stanford University in early 1999. The appearance of the CubeSat standard is associated with the need to solve one of the most important problems of training specialists in the space industry: practical work on the creation and operation of real, even the simplest, spacecraft in a short time (1-2 years) and with small budgets.

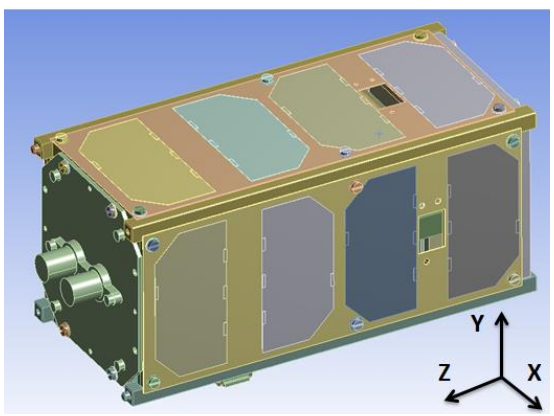
One of the most important stages in the design and ground testing, is the task of ensuring the durability of the NS, at different stages of its life cycle. The main and most responsible from the point of view of the mechanical loads acting on the NS is the stage of launching into orbit. At this stage, the NS experiences maximum quasistatic overloads [2], harmonic and random vibrations [3,5,6], impulse and acoustic effects. From the point of view of ensuring durability, the most interesting are stochastic vibrations, which can lead to the accumulation of fatigue damages and the complete or partial destruction of the NS structure. Therefore, the evaluation of NS durability in conditions of stochastic vibrations is actual topic.

The purpose of the study is calculation of the longevity of the NS PolyITAN-2-SAU on the launch phase.

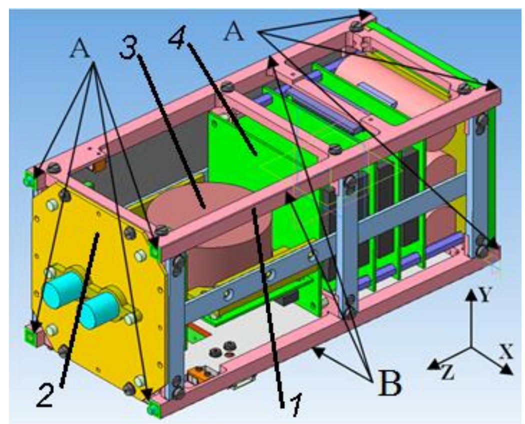
Formulation of the problem

Structural design of the NS PolyITAN-2-SAU (Fig.1) is a set of functionally related systems (power supply, control, orientation and stabilization, telemetry control, thermal management, radio engineering and scientific information collection), which are placed on a supporting frame. To supply electricity to all equipment of the NS is a power supply system.

The overall dimensions of the 3D model are 100 × 100 × 227 mm, the calculated weight is 1.8 kg [2,5].



a)



b)

Fig.1. The appearance of the NS PolyITAN-2-SAU - a) and its structural elements -b): 1 - supporting frame; 2 - scientific module; 3 – module of orientation and stabilization (SOS module); 4 - electronic platform; supporting surfaces of the supporting frame; A - face surfaces; B - lateral ribs.

The material of the supporting frame and the fasteners of the SOS - aluminum alloy D16, antenna module and elements of the Electronic Plats (EP) aluminum alloy AMg6, the set-up of EP stand-off brass L63, electronic boards, the glass-cloth KAST-B [2].

At the launch stage, the NS is located in the launch container of the P-POD launch vehicle. The lower ends of the NS is supported by a spring pusher, the upper ones on the cover of the launch container. The lateral edges of the frame (Fig. 1b) are supported by the guide rails inside the container [5].

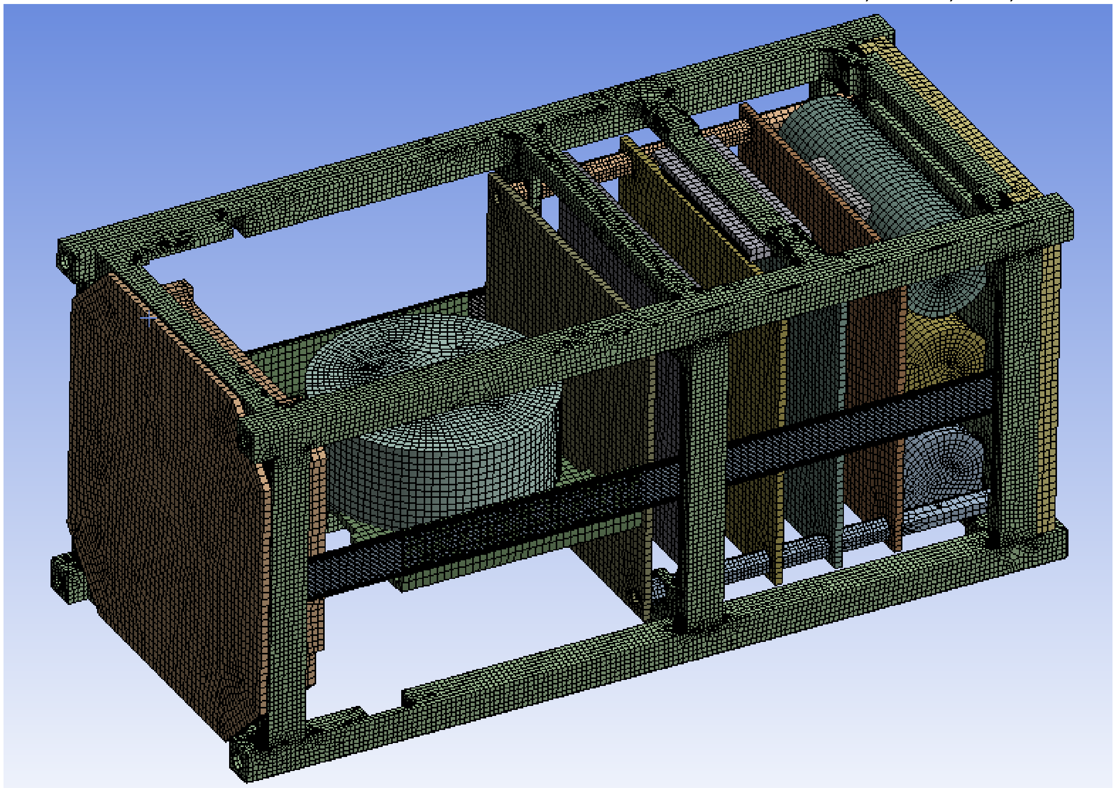


Fig.2. Finite Element Model of NA POLYITAN-2-SAU

According to [4], the strength and rigidity of the NS at the launch phase should be provided when random vibrations are applied to it in the direction of three mutually perpendicular axes X, Y, Z. Random exposure (Table 1), in the form of broadband random vibration (BRW), are transmitted to NS from the transport container P-POD through the support surfaces (Fig.1b).

Table 1. Characteristics of stationary random vibrations

Frequency, Hz	Spectral densities of accelerations $S_{xx}^{a} = S_{yy}^{a} = S_{zz}^{a}$, g^2/ Hz
20	0.01125
130	0.05625
800	0.05625
2000	0.01500

For analyzing the natural frequencies and modes of vibration, as well as the stress-strain state (SSS) of the NS under the action of random vibrations, the finite element method implemented in the ANSYS software package was used [2, 6]. For the analysis of stationary random vibrations of the NS, combination of modal coordinate methods and spectral expansions was used [5, 6].

The finite-element approximation of the 3D model of the NS generated in the ANSYS environment [2] is shown in Fig.2. When sampling the framework, the scientific module, the stacking racks of the EP, the batteries and the antenna module, 20 hexagonal finite elements (FE) (SOLID186) were used. To approximate the SOS brackets and electronic circuit boards EP, plate-like FE SHELL181 with 4 layers in thickness was used. The articulation of plate and volumetric FEs was carried out by means of massless absolutely rigid bonds based on two-node beam elements BEAM188.

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When conjugating fragments of discrete models with different partition densities, contact elements of CONTA174 were used with the same type of FE.

Determination of the Stress State Characteristics

When conducting a computational study of SSS of the NS from the effect of stationary random vibrations, the conditions for placing the NS in a shipping container were taken into account by setting the zero displacement ($u_x = u_y = u_z$) of the support surfaces of the supporting frame, with the exception of longitudinal ($u_z \neq 0$) for the side ribs [5] (Fig.1b).

The first step in the calculation is the modal analysis. The results of the modal analysis are given in Table 2. The lowest natural oscillation frequency of the NS is 222 Hz. It corresponds to the vibration shape of the electric motor in the transverse direction X (Fig. 3).

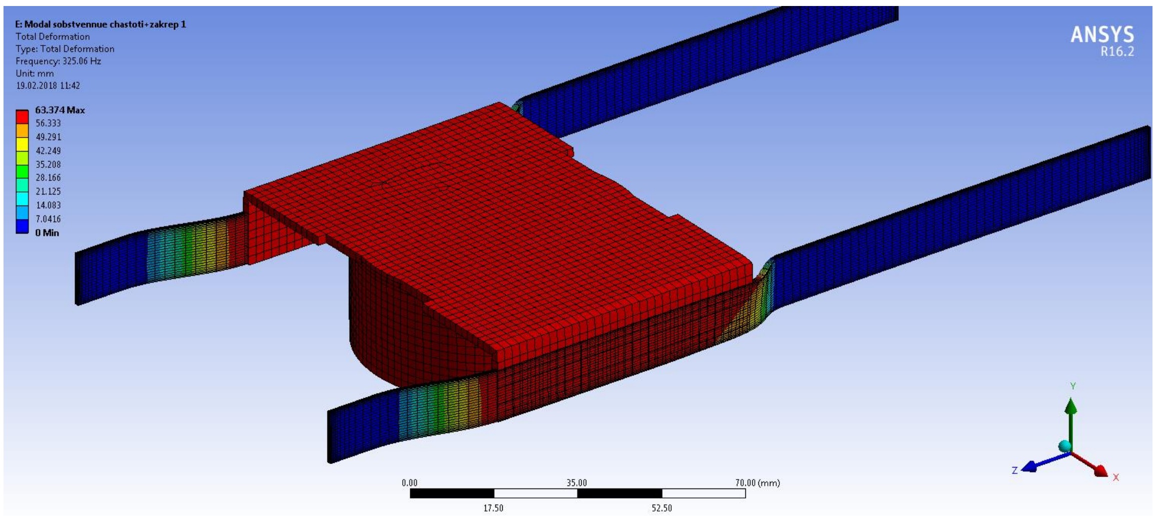

Fig.3. 1st waveform of oscillations of the NS (f = 325.06 Hz)

Table 2. The natural frequencies of oscillations of the NS

Number of the Frequency	Frequency, Hz	Number of the Frequency	Frequency, Hz
1	222.46	6	628.26
2	519.03	7	629.65
3	623.09	8	630.73
4	625.18	9	813.87
5	626.26	10	819.25

The NS loading by stationary random vibrations (Table 1) from the side of the transportation container was carried out through the bearing surfaces of the supporting frame (Fig. 1b). During the calculations, the Rayleigh damping model [5, 6] with experimentally determined damping coefficients was adopted.

The maximum RMS values of the Mises-equivalent stresses of level 3σ in NS structural elements for three loading modes are given in Table 3 [5].

It is established that the zone of the greatest stresses of the maximum RMS values is located in the bridge of the supporting frame near the fastening of the brackets of the SOS module (Fig. 4) in case of vibration loading S_{yy}^{a}. The maximum RMS of voltages corresponds to node No. 493406 of the discrete model (Fig.3).

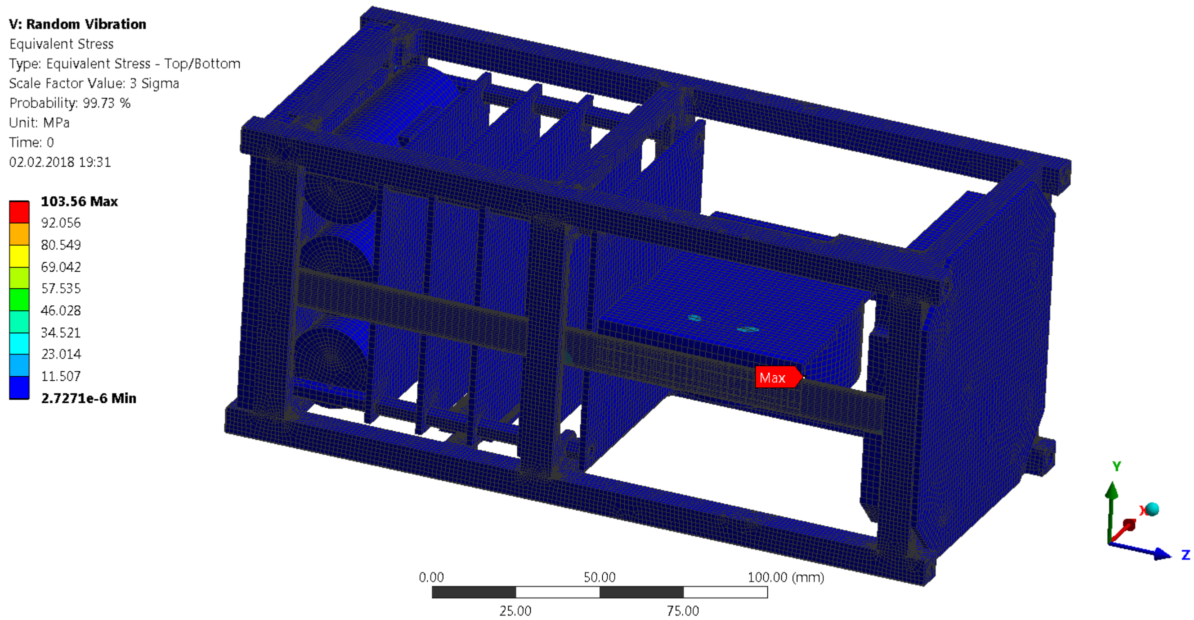

Fig.4. Distribution of RMS voltages level 3σ under the influence of random vibrations in the direction of the Y axis in the supporting frame

Table 3. The maximum RMS of voltages of level 3σ in elements NS

Direction loading / Element constructions	X	Y	Z
Carrier frame bridge	37.98	103.56	42.46
Battery holder	23.38	11.57	3.51
Type-setting EP	26.50	28.83	33.06
Baseplate EP	1.01	0.95	3.13

As a result of the computational studies, the spectral density of the equivalent voltage is determined (Fig. 5) in node No. 493406 under the influence of random vibrations in the direction of the Y-axis.

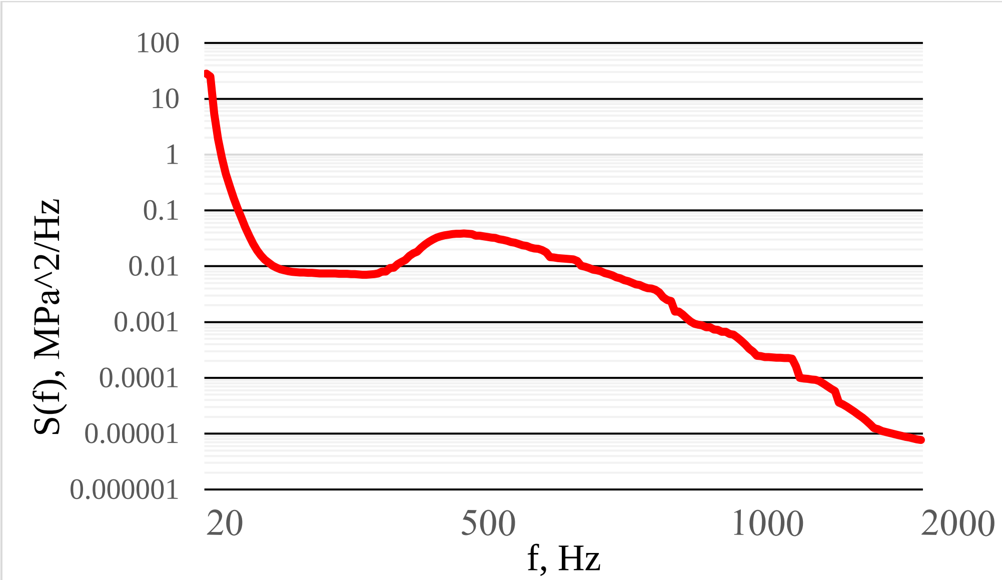

Fig. 5. Spectral power density of equivalent stresses in the node number 493406 in the logarithmic scale

Modeling of realizations of random processes of equivalent stresses

To evaluate the durability of structures affected by random vibrations, the most difficult task is to determine the processes of dynamic stress variation over time. Changes in dynamic stresses at design points are described by random functions that can be beaten either by calculating stresses at each time step, or using random stochastic modeling algorithms. The first method is applicable only for relatively simple mathematical models of constructions, since it requires repeated repetition of the solution of the quasistatic problem at each step in time.

Estimation of longevity indicators was carried out as a result of analysis of realizations of random processes of equivalent stresses at dangerous points from data of spectral characteristics.

The temporal realizations of the process of equivalent stresses corresponding to the dependences (Figure 6) are defined as a harmonic series [7]:

$$\sigma(t) = \sum_0^N [S_\sigma(\omega_j)\Delta\omega_j]^{1/2} \cos(\omega_j ' t + \alpha_j), \quad (1)$$

where ω_j is the frequency value in the graph of the spectral power density of the voltages; $S_\sigma(\omega_j)$ - the corresponding values of the power density spectral density; $\omega_j ' = (\omega_j + \delta\omega_j), \delta\omega_j$ - random fluctuations of frequency, which are defined as mutually independent random variables, uniformly distributed in the interval $[-\Delta\omega/2, \Delta\omega/2]$ with the probability density $1/\Delta\omega$; α_j are independent random variables, uniformly distributed in the interval [0, 2π]. Frequency dimension ω - rad / s.

With an increase in the number of terms N, the distribution of the values of the realizations obtained in accordance with (1) approaches the normal one [8].

The algorithm for modeling a random process (1) is implemented using the Excel system. Beforehand, in the considered frequency range (20-2000 Hz) the intervals corresponding to spectral density peaks were determined (Fig. 6). In these frequency intervals, practically the entire power of the process is concentrated. The time sampling step is selected for each frequency interval from the condition $\Delta t \leq \pi / \omega_c$ where ω_c is the upper bound of the corresponding interval.

When modeling the process of equivalent stresses in time realization, only one frequency interval of the power spectral density of equivalent stresses was used, since practically the entire power of the process: 20-161 Hz, taken $\Delta t = 0.001$ s. In Fig. 6 shows the realization of the process of stresses obtained with the help of formula (1) for the duration of the process 1c.

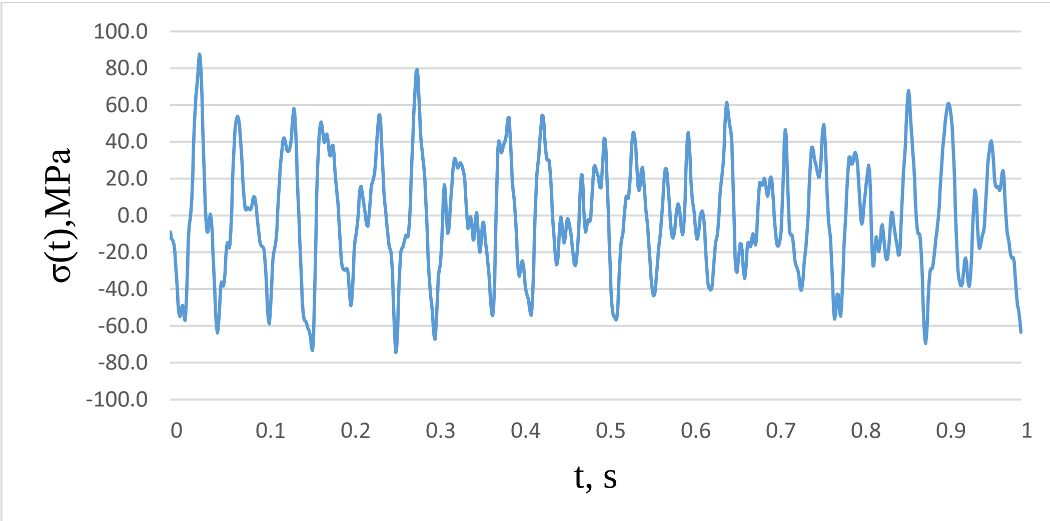

Fig. 6. Realization of the stress process T = 1c

Schematization of the loading process

To estimate the durability of the structure of the NS with random loading, the resulting random processes of equivalent stresses are reduced to a set of regular stress cycles equivalent to the damaging action, i.e. harmonic stress cycles with a constant amplitude.

In the statistical analysis of the data of temporal realizations of the process of equivalent stresses, it was assumed that this process has a normal (Gaussian) probability distribution with zero mathematical expectation. Assuming that this stress process is ergodic on the basis of the realization obtained for a single time interval, we can, according to [1], determine the number of loading cycles corresponding to the stress amplitude levels 1σ, 2σ and 3σ. Thus in Table. 4 shows the number of cycles for given constant stress amplitudes when the structure is loaded with stationary random vibrations at the launch phase.

Table 4. Repeatability of regular stress cycles over 120 s

Amplitude of the equivalent loading, MPa	Probability of the amplitude, %	*n*
0 - 34,5	68,3	4917
34,5 - 69	27,1	1951
69 - 103,5	4,33	312

Evaluation of the durability of the structures of the NS POLITAN-2-SAU

Estimating the longevity is based on the linear hypothesis of summation of damage:

$$\zeta = \sum \frac{n}{N}, \quad (2)$$

where n is the number of active load cycles; N is the number of cycles before the crack appears.

Since fatigue diagrams are constructed for standard samples of material that are subjected to certain types of laboratory tests, they have a certain shape, roughness, etc., then for the construction it is necessary to construct the reduced fatigue diagram.

The maximum RMS of the stresses equivalent in the Mises is located on the supporting frame of the NS. The material of the supporting frame is aluminum alloy D16. For a sample of this metal, it is assumed: $N_G = 3 \cdot 10^5$ cycles, $m = 4,72$, $\sigma_R = 160 MPa$ [9]. Then we can determine the ordinate of the fracture point of the reduced fatigue curve by the formula [8]:

$$\sigma_{NG_{\partial}} = \frac{\sigma_{NG}}{K} \quad (3)$$

The coefficient K entering into the relation (3) is defined as follows [8]:

$$K = (\frac{K_{\sigma}}{K_{\partial\sigma}} + \frac{1}{K_{F\sigma}} - 1) \cdot \frac{1}{K_v \cdot K_A} \quad (4)$$

Taking into account the recommendations given in [9], the coefficients of formula (4) are taken equal to: $\frac{K_{\sigma}}{K_{\partial\sigma}} = 4,2$, $K_{F\sigma} = 0,85$, $K_v = 1, K_A = 1$. Then, according to formula (4), the coefficient $K_v = 4,37$. Further, according to the formula (3) for the structure under study, the given value of the endurance limit is determined, which corresponds to the number of cycles N_G, is obtained equal $\sigma_{NG_{\partial}} = 37 MPa$. In Fig. 7 shows the fatigue curves for a sample and an element of the NS structure from material D16.

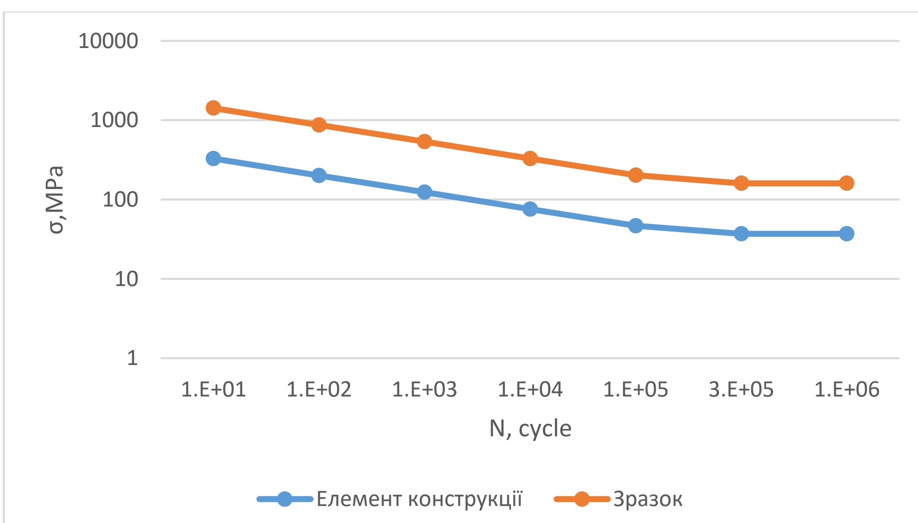

Fig. 7. Curves of fatigue life of a sample of material D16 and a structural member of nanosatellites POLYITAN-2-SAU

The definite value of the accumulated fatigue damage shows that with a vibration load for 2 min, 27.3% of the fatigue life of the structure is exhausted. This means that there is still 72.3% of durability, then according to [1], the median resource of the NS structure under conditions of stochastic vibrations, at the stage of launching into orbit, is 7 min 20 seconds.

Conclusions

Modeling of realizations of a random process of stresses is carried out. It is established that a random process of stresses is a Gaussian process with zero mean.

The fatigue curve for the most loaded element of the POLYITAN-2-SAU nanosatellite design is presented. The fracture point for this longevity curve has the coordinates $N_G = 3 \cdot 10^5$ of the cycles $\sigma_{NG_o} = 37 MPa$.

On the basis of the linear hypothesis of Mayer's accumulation of damages, damage is determined by excitation with an operational load - $\zeta = 0.273$. A certain median resource of the design of the nanosatellite POLYITAN-2-SAU under conditions of stochastic vibrations at the stage of launching into orbit is 7 minutes 20 seconds.

REFERENCES

[1] Analyzing Random Vibration Fatigue// ANSYS Advantage, Volume II, Issule 3, 2008.

[2] Tsybenko A. S. Stress-Strain State Investigation of Polyitan-2 Nano-Satellite under the Ascent-Stage Quasi-Static Overload Conditions / A. S. Tsybenko, B. M. Rassamakin, A. A. Rybalka. // Strength of Materials. – 2017. – №49. – C. 381–387;

[3] Tsybenko A. S. A Study of the Dynamic Characteristics of the Cyclone-4 Launch Vehicle on the Basis of a Continuum Rod Model / A. S. Tsybenko, A. S. Konyukhov, A. A. Rybalka. // Strength of Materials. – 2015. – №47. – C. 532–535;

[4] QB50 System Requirements and Recommendations Issue 7, 2015

[5] Tsybenko AS Analysis of the strength of the nanosatellite POLYITAN-2 under the action of random loads at the stage of launching into orbit / AS Tsybenko, BM Rassamakin, AA Rybalka. // Mechanics and Advanced Technologies. - 2017. - №81. - P. 28-33;

[6] Burlak K. P. Doslizhenna vipadkikh vibraciy nanosutputnik POLYITAN-2 / KP Burlak, AO Ribalka, OS Tsibenko. // All-Ukrainian science and technology conference for young students and students of "young people - machinebuilding". 2016.

[7] Vibration in engineering. Reference book in 6 volumes. T. 1. Oscillations of linear systems, Ed. V.V. The swamp. - Ed. The 2 nd. - Moscow: Mechanical Engineering, 1990. - 504 p. T.3. Oscillations of machines, structures and their elements, Ed. F.M. Dimentberg. K.S. Kolesnikova, 1980. - 554 p.

[8] GOST 25.504-82 Calculations and tests for strength. Methods for calculating the characteristics of fatigue resistance - M .: Publishing House of Standards, 1982. - 55 p.

[9] Troshchenko VT, Sosnovsky LA Resistance to fatigue of metals and alloys: A reference book. Parts 1 and 2 / B.T. Troshchenko. L.A. Sosnovsky. - Kiev: Naukova Dumka, 1987 - 1324 p.