Multiple robots (robotic centers) and systems. Remote sensing and non-destructive testing

Роботизированные комплексы и системы. Технологии дистанционного зондирования неразрушающего контроля

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RESEARCH ARTICLE

Diagnostics of structural integrity violations of avionics during impact tests

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Abstract

Objectives. With the continuous development of modern radio equipment in the field of aviation and space instrumentation, the requirements for accuracy, stability, and reliability of electronic equipment operated on spacecraft are also on the increase. Spacecraft avionic units (SAU) operate under special conditions and malfunctions, as a rule, are impossible to repair. SAU are hermetically sealed structures, making it difficult to assess their technical condition. The aim of this study is to increase the efficiency and reliability of detecting latent defects in SAU using the diagnostic method involving exposure to mechanical shocks.

Methods. Based on known methods, a new diagnostic method is proposed which simulates mechanical processes under shock effects at the design stage. The aim is to evaluate the presence of various latent defects in SAU. In a serviceable state, the amplitude-frequency characteristics (frequency response) of SAU differ from the frequency response of SAU with defects which affect mechanical characteristics. It was for this reason that the diagnostic model of evaluating the technical condition of SAU without removal of devices was developed.

Results. This work simulates the mechanical processes in SAU in a serviceable state in the presence of a variety of defect. It also involves experimental studies of mechanical characteristics in both serviceable and faulty states. After measuring the mechanical characteristics under the impact of shock loads, the data obtained is compared with simulation results in the presence of various defects. The comparison result is a report on the technical condition of SAU.

Conclusions. The method of diagnosing SAU under mechanical shock impact enhances the efficiency of diagnosing latent defects during the production and operation of SAU.

Keywords: diagnostics, mechanical shock impact, spacecraft avionic units

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НАУЧНАЯ СТАТЬЯ

Диагностика нарушений целостности конструкций бортовых радиоэлектронных средств при испытаниях на ударные воздействия

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Резюме
Цели. С непрерывным развитием современных технических средств в области авиации и космического приборостроения постоянно повышаются требования к точности, устойчивости и надежности электронной аппаратуры, эксплуатируемой на космических аппаратах. Блоки бортовых радиоэлектронных средств космических аппаратов (БРЭСКА) эксплуатируются в особых условиях. В случае возникновения неисправности ее устранение, как правило, оказывается невозможным. Блоки БРЭСКА представляют собой герметично закрытые конструкции, поэтому их демонтаж для оценки технического состояния затруднен. Целью исследования является повышение эффективности и достоверности выявления латентных дефектов в блоках БРЭСКА путем использования метода диагностирования при воздействии механических ударов.
Методы. На основании известных методов в работе предложен новый метод диагностирования с использованием моделирования механических процессов при ударных воздействиях на этапе проектирования блоков БРЭСКА для оценки наличия различных латентных дефектов. В исправном состоянии блоки БРЭСКА имеют амплитудно-частотные характеристики (АЧХ), отличные от АЧХ блоков БРЭСКА, имеющих различные дефекты, отражающиеся на механических характеристиках. С учетом этого разработана диагностическая модель, оценивающая техническое состояние блоков БРЭСКА без демонтажа устройств в процессе диагностирования.
Результаты. В работе проведено моделирование механических процессов в блоках БРЭСКА в исправном состоянии и при наличии различных дефектов, а также экспериментальные исследования механических характеристик в исправном и неисправном состояниях. После проведения измерений механических характеристик при воздействии ударных нагрузок полученные данные сравниваются с результатами моделирования при наличии различных дефектов. Результатом сравнения является отчет о техническом состоянии блока БРЭСКА.
Выводы. Разработанный метод диагностирования блоков БРЭСКА при ударных механических воздействиях позволяет повысить эффективность диагностирования латентных дефектов в процессе производства и эксплуатации БРЭСКА.

Ключевые слова: диагностирование, ударные механические воздействия, блок бортовых радиоэлектронных средств космических аппаратов

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INTRODUCTION

Under external destabilizing factors or in the process of aging, a change in the technical state of any radio-electronic product occurs [1, 2]. Malfunctions of spacecraft avionic units (SAU) can occur due to errors made at the stages of production or operation. These errors can result in the disruption of the physical structure and material composition, as well as in the instability of product parameters. Each error is capable of resulting in sudden or gradual failures during operation [3]. Statistics show that some electronic devices may have defects including latent ones during most of their life cycle (from production to disposal) [4–6]. Therefore, the detection and elimination of latent defects plays a very important role in maintaining the stability and performance of the equipment.[1]

The aim of this paper is to develop a new method for diagnostic modeling based on studying the SAU amplitude-frequency response (AFR) under shock impact. The simulation results along with information on the technical condition of the equipment being studied herein represent the initial data used for comparison with similar products in the absence or presence of defected SAU.

Establishing the technical condition of printed board assemblies (PBAs) or units of radio-electronic means (REM) can be performed manually using simple devices such as multimeters, oscilloscopes, and frequency meters. However, when mass inspections are required, this diagnostics process takes a lot of time and is inefficient.

Today, non-destructive methods of diagnostics are widely used at production enterprises during testing as part of the process of output control [7, 8]. Such a method for diagnosing SAU under mechanical shock loads can increase the efficiency and reliability of defect detection without disintegration of objects [9]. However, it is worth noting certain factors which need to be taken into account, in order to obtain a reliable diagnostic result:

- computer simulation of research objects must be performed with a high level of accuracy in terms of describing the physical structure, the parameters of structural materials, and materials of electro-radio elements (ERE) [10];
- support for the specified accuracy of shock simulation on the vibration test bench, and correct accelerometer placement [11].

All electronic products, whether PBA or SAU, have their own resonant frequencies.[2,3] In a good

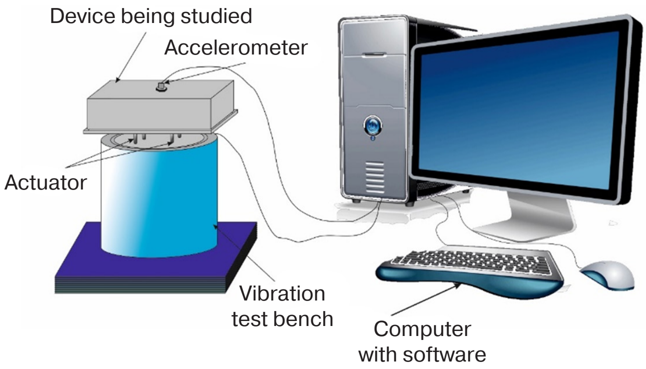

Fig. 1. The shock test bench for SAU

technical condition, the product displays a certain natural frequency spectrum. The appearance of defects in SAU is accompanied by a change in its own resonant frequencies. Based on this principle, the method of diagnostics under shock impact on SAU is proposed.[4]

A shock test bench (Fig. 1) consists of a computer system with software which analyzes technical parameters of the device under study. This system is connected to the vibration test bench, in order to determine vibration characteristics using an accelerometer. The vibrational shock effect of the vibration test bench on one axis in an upward and downward direction is recorded by a sensor. This sensor then sends this information to the computer [12]. The response produced by the vibration test bench has a certain amplitude and frequency ranging from 2 Hz to 10000 Hz. The shape of the shock can be specified as a trapezoidal, sawtooth, triangular, or half-sinusoidal pulse.

DETERMINING SAU TECHNICAL CONDITION DURING SHOCK TESTS

The aim of this paper is to determine a method for diagnosing SAU during shock tests. The structural diagram is shown in Fig. 2. The general principle of the method consists of mathematical modeling of SAU characteristics in the serviceable and faulty state. The information regarding the modeling results is used for comparison with the results obtained by experimental characterization of the real device [13, 14].

The SAU diagnostics consists of two main stages:

1. Development of a diagnostic model based on SAU characteristics and parameters and creation of a database (units 1–7). The database is a set of SAU AFRs calculated at serviceable and faulty states.

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[1] Malkin V.S. *Technical diagnostics*. 2nd ed., revised and supplemented. St. Petersburg: Lan; 2013. 272 p. (in Russ.).

[2] Zelenskiy V.A., Sukhachev K.I. *Fundamentals of design, technology and reliability of radio electronic means:* Textbook. Samara: Samara University; 2020. 146 p. (in Russ.).

[3] Muromtsev D.Yu., Tyurin I.V., Belousov O.A., Kurnosov R.Yu. *Design of functional assemblies and modules of radio-electronic means:* Textbook for Universities. 2nd ed., St. Petersburg: Lan; 2021. 252 p. (in Russ.).

[4] Muromtsev D.Yu., Belousov O.A., Tyurin I.V., Kurnosov R.Yu. *Design of REM units*. 4th ed. St. Petersburg: Lan; 2023. 288 p. (in Russ.).

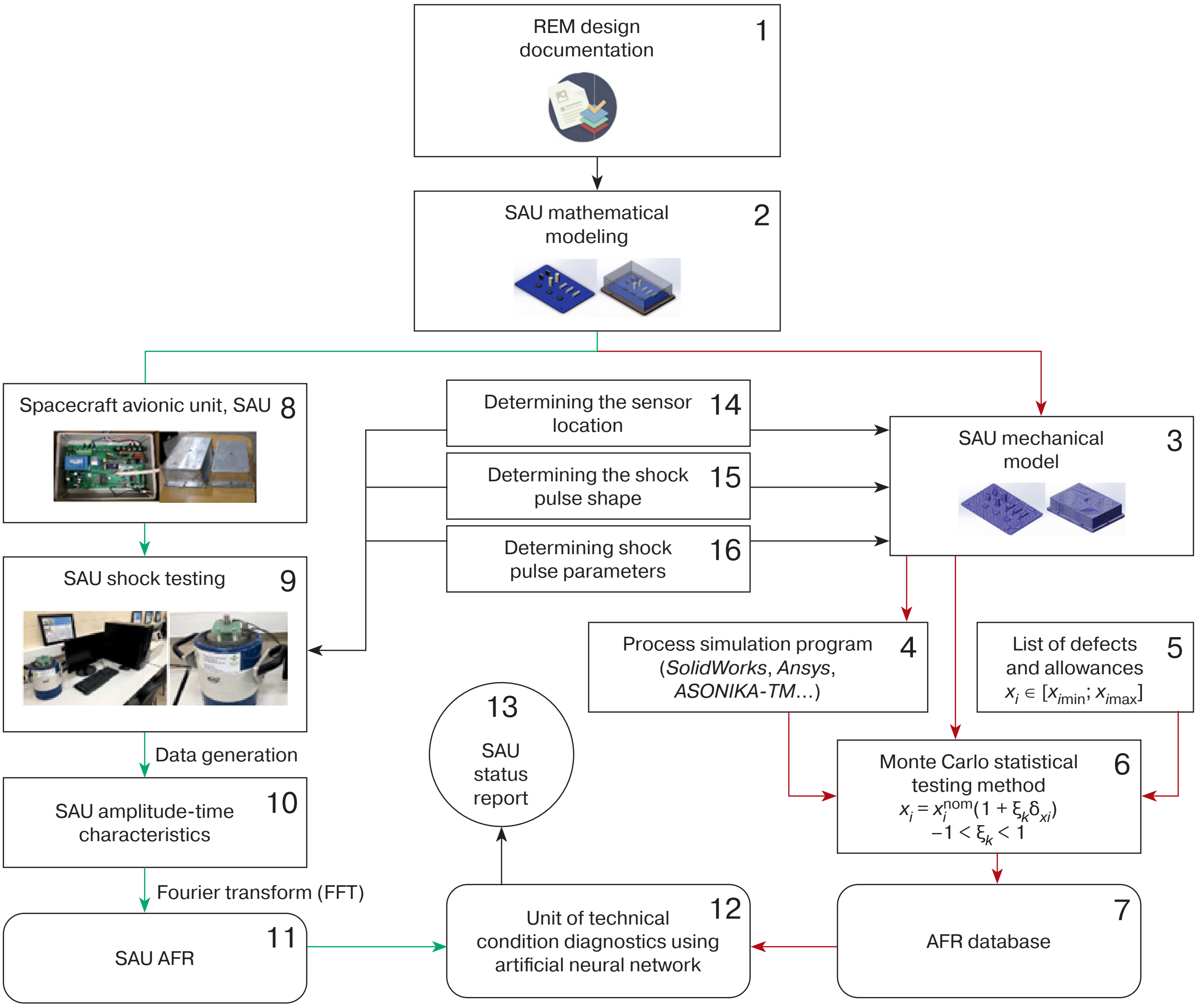


Fig. 2. Structural diagram of the method for diagnosing SAU during shock tests

2. Experimental tests of real SAU samples conducted using a vibration test bench (units 8–11). The resulting data is processed and compared (unit 12) with a set of AFR data. Then a report on the SAU technical condition is created (unit 13).

At the initial stage, the mathematical and diagnostic models of the SAU structure are developed (units 1–3 in Fig. 2). When creating the mathematical model, attention must be paid to specifying geometric and physical-mechanical parameters of the structure and EREs accurately. The placement of EREs on PBA must correspond to the given schematic diagram. During modeling, attention must be paid to the location of accelerometer on the unit, since the sensor weight can affect SAU mechanical characteristics.

Mechanical processes in SAU can be modeled using various software products, in order to establish their mechanical properties and physical structure. Such products are: *SolidWorks*[5], *Ansys*[6], *Nastran*[7], *ASONIKA-TM*[8], and others. [15]. These modeling programs allow users to obtain mechanical characteristics in SAU structures with a high level of accuracy (unit 4 in Fig. 2).

When preparing the initial data for simulating mechanical processes in SAU, the following factors must be taken into account:

- determining the sensor location, in order to obtain the result of shock impact on the object (the displacement amplitude at the sensor location is maximum at its own resonant frequency) (unit 14);

[5] https://www.solidworks.com/. Accessed December 19, 2023.
[6] https://www.ansys.com/. Accessed December 19, 2023.
[7] https://www.autodesk.com/products/nastran/overview. Accessed December 19, 2023.
[8] https://asonika-online.ru/products/asonika-tm/ (in Russ.). Accessed December 19, 2023.

- determining the pulse shape specified in the modeling program. These may be trapezoidal, triangular, sawtooth, or sinusoidal [16]. Studies have shown the trapezoidal pulse to be optimal (unit 15);
- determining pulse parameters including pulse amplitude and duration, at which the physical structure is not destroyed and SAU characteristics are not disturbed (unit 16). The value range of the pulse amplitude must correspond to the research object structure. The minimum value of the shock pulse amplitude $A_{\text{min effect}}$ must not be less than the value $A_{\text{min pract}}$ that can be obtained by the sensor. The maximum value $A_{\text{max effect}}$ should not be greater than the value of the experimental amplitude $A_{\text{min theor}}$ resulting in natural structure destruction:

$$[A_{\text{min effect}}; A_{\text{max effect}}] \in [A_{\text{min pract}}; A_{\text{max theor}}],$$

where $A_{\text{min pract}}$ is the lower boundary of amplitude values (determined by the measuring instrument characteristic); $A_{\text{max theor}}$ is the upper boundary of amplitude values.

The most common mechanical SAU defects addressed in the paper include:

- loosening of the SAU PBA screws;
- cracks in structural elements (cracking of printed circuit boards (PCBs), etc.);
- deformation of structural elements (PCB deformation, rivet fastening curvature, and etc.);
- tearing off a part of or the whole ERE from PBA;
- passive ERE contact on the printed circuit board with other structural elements (may occur in conditions of the SAU high density).

The calculation result of the diagnostic model for mechanical processes is a set of SAU AFRs for specified typical defects stored and presented on the computer (unit 7 in Fig. 2). Each AFR corresponds to a certain faulty state or its set of defects.

In the aims of enhancing diagnostic efficiency and reducing the probability of errors (incorrect defect recognition, non-existent defects) [17], the simulated mechanical processes take into account allowances $[x_{i\text{min}}; x_{i\text{max}}]$ within which the values x_i, $i = \overline{1, n}$ for physical-mechanical and geometric parameters of structural elements change (unit 6 in Fig. 2). Here, the Monte Carlo simulation modeling method is used [18]. Thus, the parameter value (physical-mechanical or geometric) for the SAU structure is determined using the following formula:

$$x_i = x_i^{\text{nom}}(1 + \xi_k \delta_{xi}),$$

where x_i is current value of the ith parameter at kth realization; x_i^{nom} is nominal value of the ith parameter; ξ_k is random variable ($-1 < \xi_k < 1$) output by the random number generator; δ_{xi} is relative allowance of the ith parameter. At the final stage, experimental SAU characteristics are determined. The experiment is conducted on the vibration test bench (unit 9 in Fig. 2) integrated with a computer to obtain the product AFR through the sensor installed in the center of the SAU cover (unit 10 in Fig. 2).

The resulting characteristic is the data set of discrete AFR values used to calculate the transition from the time domain to the frequency domain via the fast Fourier transform (FFT) (unit 11). Fast Fourier transform formula is the following:

$$F(\omega) = \int_{-\infty}^{+\infty} f(t)\mathrm{e}^{-j\omega t}dt,$$

where t is time, $f(t)$ is the normal distribution density function, ω is the signal cyclic frequency, and j is the imaginary unit.

This result is used for comparison with the previously created AFR set (unit 7) using an artificial neural network applied to the search task (ensemble learning introduced neural network) implemented in the Python language environment.

As a result, a report on SAU technical condition is created. When defects are detected using the described methodology, they can be remedied at the production enterprise. Should SAU AFR not coincide with any AFR stored in the database prior to defect confirmation, additional research or final expert decisions will be required.

The diagnostic result using this method may be achieved with a high level of efficiency in the case of simulation modeling of a large defect database. It also provides a high level of accuracy when setting geometric and physical-mechanical parameters of SAU design. In addition, it increases the economic efficiency of diagnostics when used in serial production.

EXPERIMENTAL STUDIES OF THE PROPOSED METHOD

In order to verify the proposed method, an experimental SAU prototype was created.[9] It represents a closed body with dimensions shown in Fig. 3. The unit body is made of pressed aluminum. The body elements are fastened together using screw connections.

Inside the body, the printed circuit board (WAVGAT authorization Store, China) of 100 × 150 mm in size is placed on a fixed stand using a retaining screw (Fig. 4).

[9] GOST R 52762-2007. National Standard of the Russian Federation. *Mechanical environment stability test methods for machines, instruments and other industrial products. Test methods for bumps to enclosure of products*. Moscow: Standardinform; 2007. 19 p. (in Russ.).

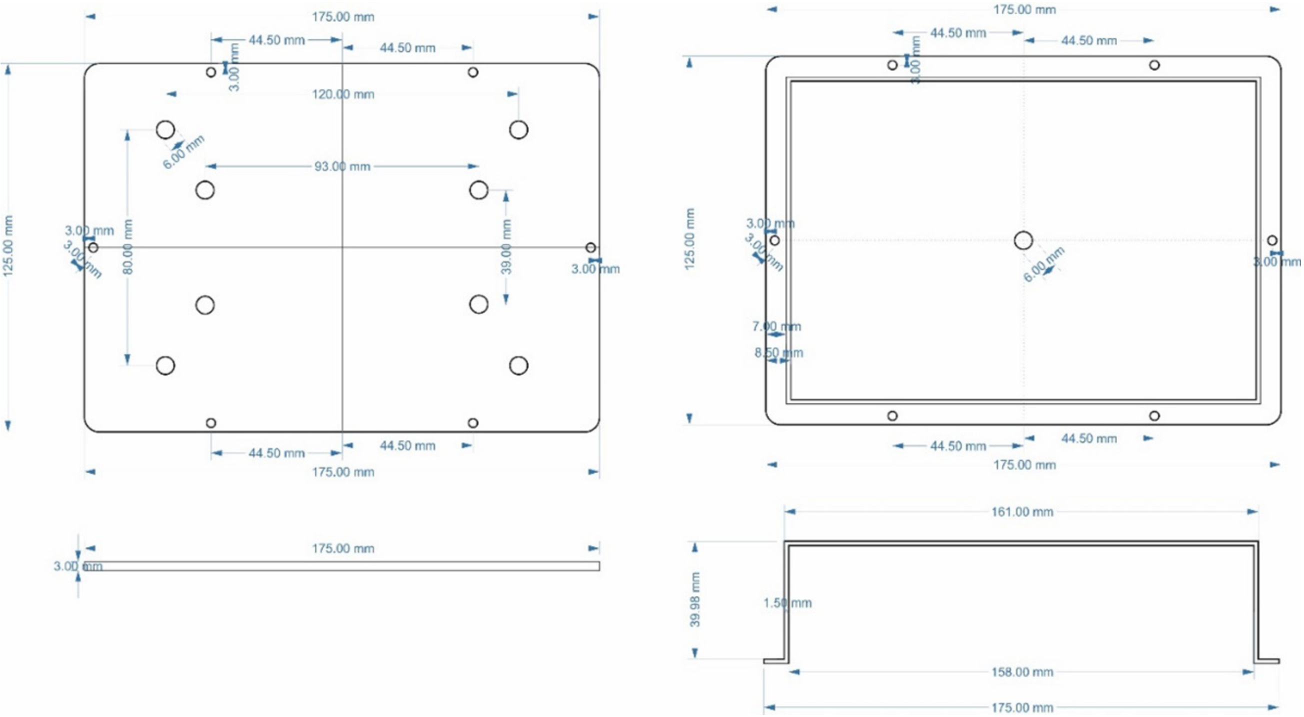
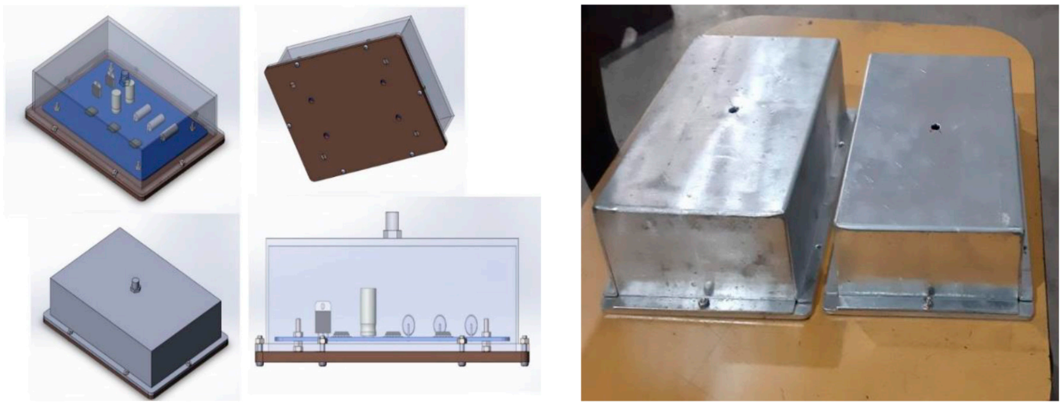


Fig. 3. Drawing of SAU body (bottom and cover)



(a) (b)

Fig. 4. View of SAU model (a) and the real sample (b)

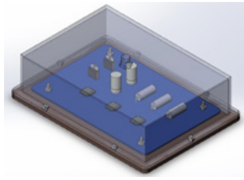
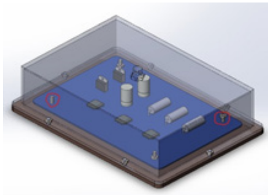
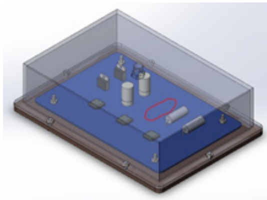
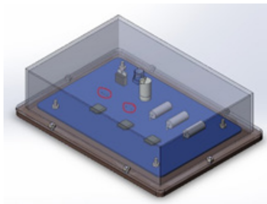
The device being studied is placed on a vibration test bench (IMV Corporation, Japan) connected to the computer by means of software (Fig. 5). The sensor used to measure SAU mechanical characteristics refers to the VP-32 type.[10]

Experimental studies of SAU are carried out under trapezoidal impulse shock with acceleration $A = 30$ m/s^2, shock duration $T = 0.04$ s. Possible defects are described in Table 1.

Fig. 5. The appearance of the vibration test bench

[10] https://ostec-test.ru/catalog/equipment/datchiki-vibratsii/vibropreobrazovatel-uskoreniya-vp-32/ (in Russ.). Accessed December 19, 2023.

Table 1. Description of SAU defects

Defect	Defect description	Image
No defects	Serviceable state	
Defect 1	Loosening of PBA screws	
Defect 2	Absence of resistor	
Defect 3	Absence of transistor and capacitor	

The experimental measurement results of the mechanical characteristics obtained on the SAU prototype represent AFR for each of its defects (Fig. 6). This shows a distinct AFR result: the natural resonant frequency values at the control point, where the sensor is installed, for SAU with a defect differ from those in the serviceable state. The results are recorded in the AFR database for SAU different technical states (Table 2). They can be used for diagnostic analysis of SAU technical condition in the future.

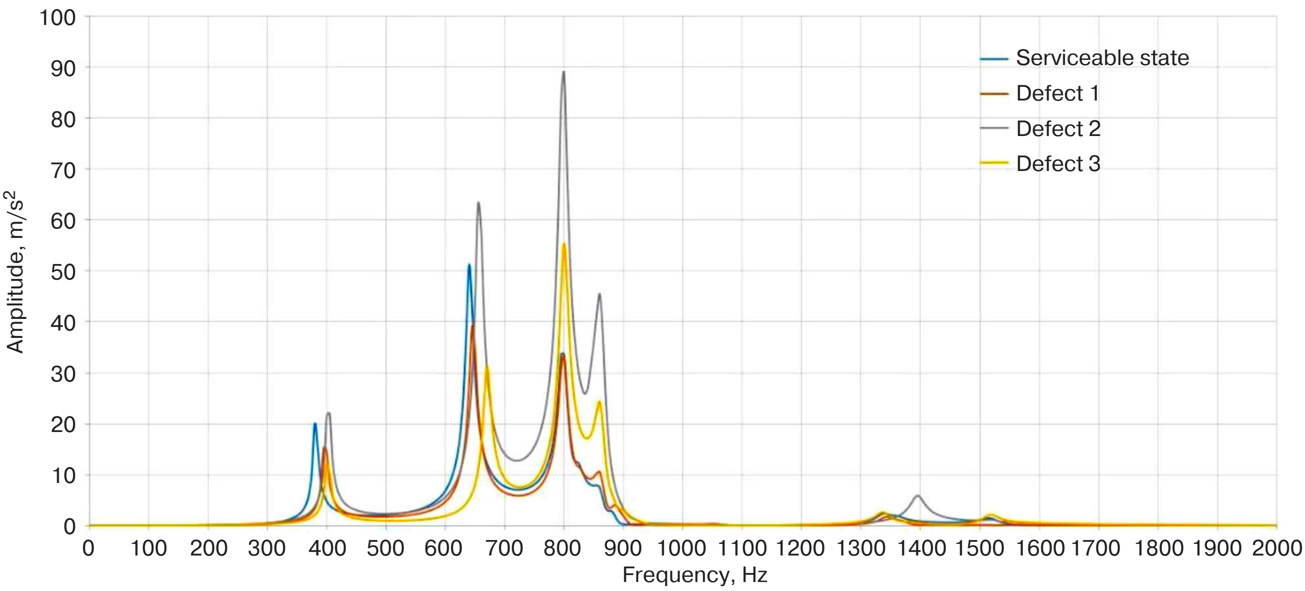


Fig. 6. Spectral characteristics for differing SAU states

Table 2. Database for SAU different states

Frequency, Hz	Serviceable state	Defect 1	Defect 2	Defect 3
0	0.0038	0.0024	0.0023	0.0021
5	0.0038	0.0024	0.0024	0.0022
10	0.0038	0.0024	0.0023	0.0021
15	0.0037	0.0023	0.0021	0.0020
20	0.0034	0.0022	0.0018	0.0018
25	0.0031	0.0020	0.0014	0.0014
30	0.0028	0.0017	0.0010	0.0011
……	…………	…………	…………	………….
1970	0.0089	0.0166	0.0770	0.0694
1975	0.0087	0.0162	0.0749	0.0675
1980	0.0085	0.0158	0.0729	0.0656
1985	0.0083	0.0153	0.0708	0.0637
1990	0.0081	0.0149	0.0688	0.0618
1995	0.0079	0.0145	0.0668	0.0600
2000	0.0077	0.0140	0.0648	0.0582

CONCLUSIONS

The method for diagnosing SAU under mechanical shock loads proposed in this paper allows for SAU defects to be diagnosed and detected efficiently. Further studies will facilitate the detection of all possible types of defects using this method, and can assist in developing both an algorithm and diagnostic techniques. The research results could be implemented into the educational process of MIREA – Russian Technological University and other universities.

Authors' contribution. All authors equally contributed to the research work.

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