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RESEARCH ARTICLE

Calculating permissible deviations of vibration accelerations of printed circuit assemblies by simulation modeling

Vladimir K. Bityukov,
Aleksey V. Dolmatov @,
Anatoly A. Zadernovsky,
Anatoly I. Starikovsky,
Ruslan M. Uvaysov

MIREA – Russian Technological University, Moscow, 119454 Russia
@ Corresponding author, e-mail: dolmatov@mirea.ru

Abstract
Objectives. A variety of technical condition control methods are used in the production and operation of printed circuit assemblies (PCA) for radio-electronic means (REM). The main methods are optical, electrical, and thermal. However, not all possible defects can be detected using these methods. For example, a weakened PCA fastener in a block or the incorrect installation of an electric radioelement (ERE) on a printed circuit board (PCB) can be detected only by analyzing the mechanical characteristics of the REM. These factors, in particular, are the values of the vibration acceleration amplitudes on ERE or at selected PCB control points (hereinafter referred to as the PCA vibration acceleration amplitude). In order to draw a conclusion about the presence of a defect, the measured values of the vibration acceleration amplitudes obtained as a result of testing PCA for the effects of harmonic vibration are compared with the permissible values calculated during the simulation of mechanical processes in PCA. This takes into account the variations in the physical and mechanical parameters of materials and geometric parameters of the PCA design. The aim of this paper is to determine the permissible values of PCA vibration acceleration amplitudes to be compared with the measured values.
Methods. The Monte Carlo simulation method is used to calculate the permissible deviations of vibration accelerations. This consists in repeatedly calculating the values of the vibration acceleration amplitudes at random values of the physical and mechanical parameters of materials and geometric parameters of the PCA design within their tolerances.
Results. Experimental verification of this method was carried out using the *SolidWorks* software for modeling mechanical processes. This enabled the tolerance values for PCA vibration acceleration at the control point at the first resonant frequency to be established and experimental data to be obtained when introducing various defects. The results of comparing the measured values with the calculated tolerance enabled conclusions to be made with regard to the possibility of detecting PCA defects.
Conclusions. Using this method of calculating tolerances for the PCA vibration acceleration amplitude allows the presence of defects in REM that do not affect the electrical or thermal characteristics of REM to be determined, thus increasing the efficiency of technical condition control.

Keywords: non-destructive testing, simulation modeling, Monte Carlo method, printing circuit boards, electronic means, mechanical processes

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НАУЧНАЯ СТАТЬЯ

Расчет допустимых отклонений виброускорений печатных узлов методом имитационного моделирования

В.К. Битюков,
А.В. Долматов @,
А.А. Задерновский,
А.И. Стариковский,
Р.М. Увайсов

МИРЭА – Российский технологический университет, Москва, 119454 Россия
@ Автор для переписки, e-mail: dolmatov@mirea.ru

Резюме
Цели. При производстве и эксплуатации печатных узлов (ПУ) радиоэлектронных средств (РЭС) используются различные методы контроля технического состояния. Основные из них – это оптический, электрический и тепловой. Но не все возможные дефекты выявляются с использованием указанных методов. Например, ослабленное крепление ПУ в блоке или некорректная установка электрорадиоэлемента (ЭРЭ) на печатной плате выявляются только путем анализа механических характеристик РЭС, в частности значений амплитуд виброускорений на ЭРЭ или в выбранных контрольных точках печатной платы (далее – амплитуда виброускорения ПУ). Чтобы сделать вывод о наличии дефекта, измеренные значения амплитуд виброускорений, полученные в результате испытаний ПУ на воздействие гармонической вибрации, сравниваются с допустимыми значениями, рассчитанными при имитационном моделировании механических процессов в ПУ с учетом разбросов физико-механических параметров материалов и геометрических параметров конструкции ПУ. Цель работы состоит в определении допустимых значений амплитуд виброускорений ПУ, с которыми будут сравниваться измеренные значения.
Методы. Для расчета допустимых отклонений виброускорений предлагается использование метода имитационного моделирования Монте-Карло, заключающегося в многократном расчете значений амплитуд виброускорений при случайных значениях физико-механических параметров материалов и геометрических параметров конструкции ПУ в пределах своих допусков.
Результаты. В результате экспериментальной проверки описанного метода с помощью программы моделирования механических процессов *SolidWorks* определены значения допуска на виброускорения ПУ в контрольной точке на первой резонансной частоте и получены экспериментальные данные при внесении различных дефектов. Результаты сравнения измеренных значений с рассчитанным допуском позволяют сделать вывод о возможности обнаружения дефектов ПУ.
Выводы. Использование данного метода расчета допусков на амплитуду виброускорения ПУ позволяет определять наличие дефектов в РЭС, которые не влияют на электрические или тепловые характеристики РЭС, и таким образом повысить эффективность контроля технического состояния.

Ключевые слова: неразрушающий контроль, имитационное моделирование, метод Монте-Карло, печатный узел, радиоэлектронное средство, механические процессы

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INTRODUCTION

Modern radio-electronic means (REM) are complex devices, both in terms of electrical circuits and in terms of design. A wide variety of circuit and design solutions,[1] as well as materials used in REM production[2] can cause the presence of deviations in their characteristics from their nominal values. As a rule, the technical condition of REM can be diagnosed [1, 2] by electrical, thermal, and mechanical characteristics.[3] Methods for diagnosing electrical and thermal characteristics are fairly well developed and elaborated [3–6], while diagnostics by mechanical characteristics still remains relevant due to the difficulties in controlling mechanical characteristics and the variety of mechanical connections present in modern REM designs [7–9].

Despite the high requirements for the quality and reliability of products at the production stage, there is a probability of various defects such as: deformation of electro-radio elements (ERE); weakening of their fasteners or printed circuit board (PCB); formation of cracks in PCB, which to a certain extent would affect the mechanical mode of operation and may result in REM failure.

The production stage of printed circuit assemblies (PCA) is completed by testing, in order to confirm their reliability throughout their life cycle. Depending on the REM specifics, they are subjected to a large number of different *in situ* tests[4] [10]. The vast majority of REMs are tested for mechanical effects: primarily vibration [11–13]. In this case, the measured characteristics are compared with the maximum permissible, in order to assess the vibration resistance of REM [14]. However, a number of defects (e.g., PCA weakened mounting, ERE incorrect installation, etc.) may not lead to the measured value of the mechanical characteristic exceeding the maximum permissible value. They may, however, result in REM failures during operation. Therefore, the paper proposes that the measured values of mechanical characteristics be compared with the values of their tolerances due to the variation of physico-mechanical and geometric parameters of REM materials. This will enable a conclusion about REM technical condition based on the results of comparison to be drawn.

METHOD FOR CALCULATING PERMISSIBLE DEVIATIONS OF PCA VIBRATION ACCELERATIONS

One of the technical condition control methods necessary to ensure high reliability of REM involves non-destructive testing by mechanical characteristics. This is based on a comparison of values of the ERE vibration acceleration amplitudes and in PCB control points of the tested PCA and the PCA reference sample. The presence of defects in PCA results in the deviation of the ERE vibration acceleration amplitudes from their nominal values, both higher and lower.

The PCA vibration acceleration amplitude depends on the physico-mechanical parameters of PCA materials, geometric parameters of PCA structural elements, and PCA fastening points.

To control PCA by mechanical characteristics, a reference mechanical model needs to be created, the calculation results of which would be used for comparison with the measured values of vibration acceleration amplitudes of the studied PCA samples. In order to create the mechanical model, a variety of programs can be used to model the mechanical processes in REM. The accuracy of modeling PCA mechanical characteristics is determined by many factors. These include: correctness and completeness of describing the topological model of mechanical processes; precisely describing fastening conditions; as well as setting such values of physico-mechanical parameters of materials and geometrical dimensions of construction elements which correspond to real values as much as possible. Practice shows

[1] Muromtsev D.Yu., Tyurin I.V., Belousov O.A., Kurnosov R.Yu. *Design of functional units and modules of radioelectronic devices:* A textbook for universities. 2nd ed. St. Petersburg: Lan; 2021. 252 p. (in Russ.).

[2] Pokrovskaya M.V., Popova T.A. *Materials and structural elements of REM:* A textbook. Moscow: RTU MIREA; 2021. Part 1: Material science and structural materials. 200 p. (in Russ.).

[3] Davydov P.S. *Technical diagnostics of radioelectronic devices and systems*. Moscow: Radio and Communications; 1988. 256 p. (in Russ.).

[4] Baranov V.M., Karasevich A.M., Sarychev G.A. *Testing and quality control of materials and structures*: A textbook for universities. Moscow: Higher School; 2004. 359 p. (in Russ.).

that for the majority of engineering calculations the modeling error of mechanical characteristics is no more than 30% for preliminary calculations and about 5–10% for calculations with refined data.

Initial data on the values of physico-mechanical parameters of REM materials necessary for modeling mechanical processes, as indicated in a range of reference books, can be obtained as a rule from experimental studies and set in a certain range of values. The model of mechanical processes in PCA, analyzed by specified physico-mechanical parameters of materials and with experimentally investigated distribution of PCA ERE vibration acceleration amplitudes, can be taken as a reference model. This model can also be used for technical condition control during experimental tests of PCA samples.

When using the reference mechanical model of PCA, the tolerances for the values of ERE vibration acceleration amplitudes are calculated using the program for modeling mechanical processes. Based on the results, the maximum permissible value $a^{\max}$ and minimum permissible value $a^{\min}$ of vibration acceleration amplitudes for each ERE can be determined. These modeling results form the basis for comparison with experimentally obtained values, wherein the deviations beyond the tolerance limits are considered as various kinds of defects [2].

In order to determine the PCA suitability for operation, the tolerance interval $[a_{\mathrm{PCA}\ m}^{\min}, a_{\mathrm{PCA}\ m}^{\max}]$ needs to be calculated for each mth control point of the vector of vibration acceleration measured values $\overline{a_{\mathrm{PCA}\ m}}$ PCA would be considered serviceable, if the following condition is met:

$$\overline{a_{\mathrm{PCA}\ m}} \in \left[a_{\mathrm{PCA}\ m}^{\min}, a_{\mathrm{PCA}\ m}^{\max}\right].$$

When controlling PCA technical condition, the minimum permissible value $a_{\mathrm{PCA}\ m}^{\min}$ and the maximum permissible value $a_{\mathrm{PCA}\ m}^{\max}$ of PCA vibration acceleration amplitudes are used, while the maximum value $a_{\mathrm{PCA}\ m}^{\max}$ can be used to calculate reliability factors.

After calculating the PCA reference mechanical model, vibration accelerations are measured in the control points of the studied PCA group using vibration detectors. The values of the PCA vibration acceleration amplitudes obtained as a result of measurements are compared with their maximum permissible values. Then a conclusion about the PCA technical condition is made on the basis of the comparison results. The values of vibration acceleration amplitude of elements for serviceable PCA samples should lie within the range of values obtained by calculating the reference mechanical model. A PCA sample with a deviation of PCA vibration acceleration amplitude beyond the calculated limits detected is considered defective.

The PCA reference mechanical model is obtained at parameter values of REM designs lying within their tolerances. However, the mechanical model can also be used to form a fault base which can form a reference book of the vibration acceleration amplitude distribution over the PCA surface in the presence of any defect. Such a reference book is formed in advance before PCA diagnostics. Applying this method allows defects related to the ERE installation, as well as defects related to PCB production.

Thus, the PCA reference mechanical model takes two factors into account: the spread of various parameters (physico-mechanical parameters of materials, geometric parameters of designs) within their tolerances when using the model to search for defective products; and the possible presence of typical defects in PCA when using the model to identify defects in the studied PCA.

In some cases, the existing models and methods for calculating the mechanical modes of REM designs do not allow the influence of physico-mechanical parameters of REM design materials and geometrical parameters of REM designs on the mechanical mode of the product to be analyzed in detail. The Monte Carlo method of statistical testing used for modeling various physical processes in REM, in particular, mechanical processes in PCA design and REM as a whole, is highly capable of resolving this problem [15, 16]. The advantages of the Monte Carlo method over other methods of studying physical processes offer a fairly simple mathematical apparatus of calculations, as well as a clear physical interpretation of the considered problem. These factors thus simplify the programming process and provide ease of control at the stage of program debugging.

When applying the Monte Carlo method, a special random number generator program is used. This program repeatedly outputs random values of a certain quantity distributed in accordance with the specified distribution law. For each random variable value, the values of REM mechanical characteristics are determined. This calculation is repeated a number of times as specified by the user. For each calculation, the values of the model parameters take random values lying within their tolerances. Based on modeling results, histograms showing the laws of distribution of mechanical characteristics are built. Then the mathematical expectation and standard deviation of the PCA vibration acceleration amplitudes are calculated from these.

The applied method does not require parametric sensitivity functions to be calculated. However, it requires a large amount of machine time depending on the complexity of the mechanical model and the number of iterations. At the same time, the error of the method is usually of the order of 10%.

Figure 1 shows the flow diagram of the method for calculating the maximum permissible values of the ERE vibration acceleration amplitude using simulation modeling of mechanical processes.

When modeling using this method, such factors as deviations physico-mechanical parameters of materials and geometrical parameters of REM design within their tolerances are taken into account. The use of simulation modeling allows a lot of statistical information to be collected. In this way the permissible variation of ERE vibration accelerations can be determined.

The input data for modeling is:

- the description of REM design;
- $q_{mi}^{min}, q_{mi}^{max}$ being minimum and maximum values of the *i*th physico-mechanical parameter of REM design, respectively;
- $q_{gj}^{min}, q_{gj}^{max}$ being minimum and maximum values of the *j*th geometric parameter of REM design, respectively.

Using the program for modeling the mechanical modes of REM operation, a multiple (*N* times) mechanical calculation of REM design containing PCA (the block, as a rule) is carried out at the first stage. This calculation is performed, in order to determine the spread in vibration acceleration amplitudes in PCA fastening points.

The parameter nominal value can be determined from the minimum and maximum limits of its actual value spread range, taking into account the normal law of parameter distribution according to the following equation:

$$q^{nom} = (q^{max} + q^{min})/2.$$

The relative tolerance value for the parameter value is determined by the following equation:

$$\delta = (q^{max} - q^{min})/q^{nom}.$$

The values of physico-mechanical parameters of materials (q_m) and geometric parameters of designs (q_g) for each implementation of the Monte Carlo method take random values within their tolerances. These take into account the value of random variable ξ_n in accordance with the following equations:

$$q_m = q_m^{nom}(1 + \xi_n \delta_m), \ \ q_g = q_g^{nom}(1 + \xi_n \delta_g).$$

The random variable ξ_n values are generated according to the normal law of distribution of the random variable with zero mathematical expectation and standard deviation $\sigma = 0.33$. The truncated normal distribution of variable ξ_n on the interval $\pm 3\sigma$ is derived.

After performing *N* calculations of the mechanical mode of PCA design, *N* values of vibration acceleration amplitudes (a_f) in PCA fastening points are obtained. According to these values, the mathematical expectation of the vibration acceleration amplitude in each PCA fastening point $m(a_f)$ can be determined as follows:

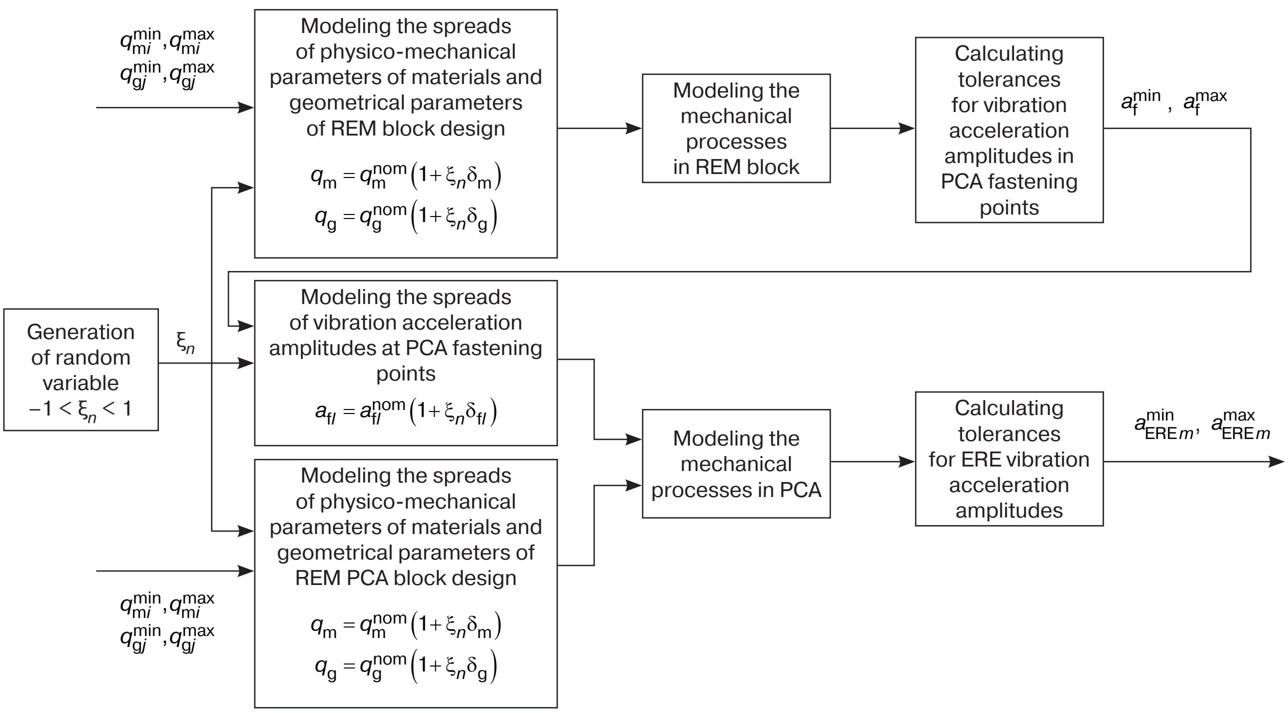


Fig. 1. Flow diagram of the method for calculating permissible deviations of PCA vibration accelerations. $a_{fl}^{nom} = (a_{fl}^{min} + a_{fl}^{max})/2$. $a_{EREm}^{min}, a_{EREm}^{max}$ are tolerances for ERE vibration acceleration amplitudes

$$m(a_f) = \frac{\sum_{n=1}^{N} a_f^n}{N},$$

where a_f^n is value of the vibration acceleration amplitude at the PCA fastening point on the nth implementation.

The dispersion of vibration acceleration $D(a_f)$ is determined by the following equations:

$$D(a_f) = \frac{\sum_{n=1}^{N}\left(a_f^n - m(a_f)\right)^2}{N-1}$$

or

$$D(a_f) = \left(\frac{\sum_{n=1}^{N}\left(a_f^n\right)^2}{N} - \left(m(a_f)\right)^2\right)\frac{N}{N-1}.$$

The standard deviation $\sigma(a_f)$ of the vibration acceleration amplitude at the PCA fastening point is calculated by the following equation:

$$\sigma(a_f) = \sqrt{D(a_f)}.$$

In order to determine the range of permissible values of vibration acceleration amplitude $[a_f^{\min}, a_f^{\max}]$, confidence probability β should be specified as follows:

$$\beta = P\left(a_f^{\min} \le a_f \le a_f^{\max}\right),$$

with which the actual value of vibration acceleration amplitude may lie within this range. Taking into account the value of probability β, the value of coefficient χ is determined according to the reference data. For example, for a confidence probability value β = 0.9973, the value of coefficient χ is equal to 3.

The minimum value $a_f^{\min}$ and the maximum value $a_f^{\max}$ of the vibration acceleration amplitude taking into account the value coefficient χ for a given probability β are calculated according to the following equations:

$$a_f^{\min} = m(a_f) - \chi\sigma(a_f),\ \ a_f^{\max} = m(a_f) + \chi\sigma(a_f).$$

As the result of calculating the mechanical mode of the block, the range $[a_f^{\min}, a_f^{\max}]$ within which the vibration acceleration amplitude values may lie at PCA fastening points can be determined.

Then the statistical modeling of mechanical processes in PCA is carried out in the same way. This involves randomly specifying the values of vibration acceleration amplitude at PCA fastening points from the range $[a_f^{\min}, a_f^{\max}]$, as well as the values of physico-mechanical parameters of PCB material and geometrical parameters of PCA design from the range of possible values. The modeling thus determines the range $[a_{\text{PCA}\,m}^{\min}, a_{\text{PCA}\,m}^{\max}]$ within which the values of ERE vibration acceleration amplitudes for serviceable PCAs lie.

The process of PCA control by mechanical characteristics imposes increased requirements to the reliability of modeling mechanical modes in PCA. When building a model of mechanical processes, certain assumptions also need to be taken into account when analyzing the modeling results.

The error Δ_a^{calc} of calculating the ERE vibration acceleration amplitudes is determined by the following equation:

$$\Delta_a^{\text{calc}} = \sqrt{\Delta_m^2 + \Delta_g^2 + \Delta_s^2 + \Delta_\xi^2},$$

where Δ_m is the error at which physico-mechanical parameters of REM design materials are specified; Δ_g is the error at which geometrical parameters of REM design are specified; Δ_s is the error depending on the computational grid step; Δ_ξ is the error determined by the number of the Monte Carlo method implementations.

The error in determining the maximum permissible deviations of ERE vibration acceleration amplitudes is determined by the number of implementations N in the Monte Carlo method, in addition to error Δ_a^{calc} introduced by various assumptions when creating the mechanical model. The relative error related to the number of implementations can be determined by the following equation:

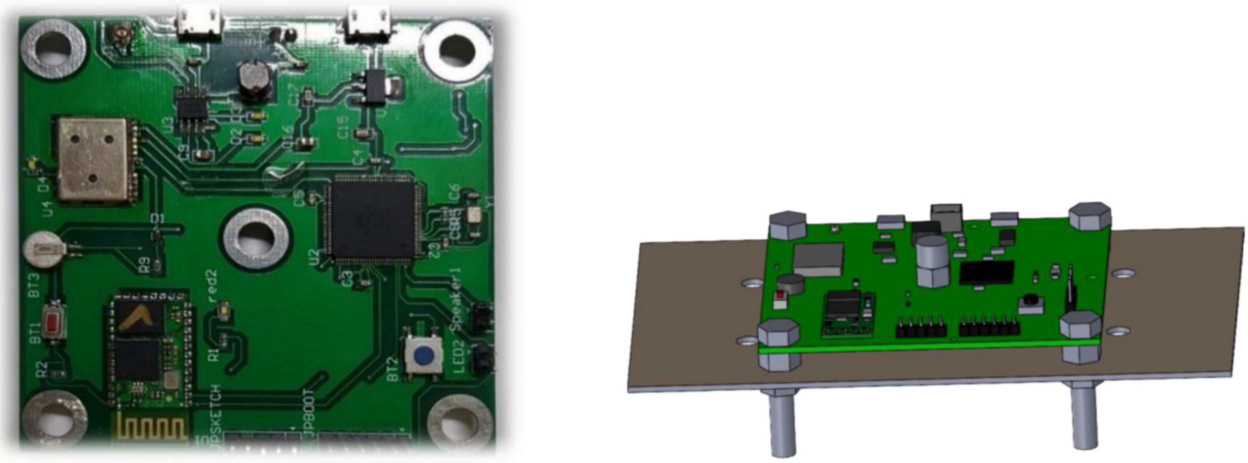
$$\Delta_\xi = 3\sqrt{\frac{D(\xi)}{N}}.$$

It is very important to ensure the accuracy of modeling mechanical processes, since the result of PCA control by mechanical characteristics depends on it. An incorrect result may lead to "rejecting" the serviceable product or to missing the product with a defect posing serious consequences in its operation.

In order to apply this method, a variety of programs for modeling mechanical processes in REM designs of different hierarchy levels, such as *ASONIKA-TM*[5], *SolidWorks*[6], etc., may be used [17, 18].

[5] https://asonika-online.ru/products/asonika-tm/ (in Russ.). Accessed June 15, 2023.

[6] https://www.solidworks.com/. Accessed June 15, 2023.



(a) (b)

Fig. 2. The PCA (a) and its model in *SolidWorks* software (b)

EXPERIMENTAL VERIFICATION OF THE METHOD FOR CALCULATING PCA VIBRATION ACCELERATION TOLERANCES

For the experimental verification of the method described, an onboard radio-electronic device for controlling run-up parameters is used. This device is a PCB with the following EREs installed upon it: Atmel ATmega2560 microcontroller (Atmel Corporation, USA); InvenSense MPU-6050 accelerometer (InvenSense Inc., USA); Global Navigation Satellite System receiver U-blox Neo 7M (U-blox, Switzerland), Bluetooth chip HC-05 (Core Electronics, China); and AMS1117-3.3 power supply (UMW, China).

In order to calculate tolerances for the vibration acceleration amplitude value, PCA mechanical processes are simulated using *SolidWorks* software. The PCA and its model are shown in Fig. 2.

During modeling, the spread of PCB material density 1500–1800 kg/m^3 and elastic modulus 22–26 GPa is set. The number of the Monte Carlo method implementation is 500. As a result of modeling, the spread of the PCA vibration acceleration amplitude is obtained at the PCA control point in a serviceable condition at the first resonant frequency whose value is 170 Hz. The control point is located in the center of PCB and is selected by the results of analyzing distribution of vibration acceleration values on PCB based on the maximum value. The spread of vibration acceleration amplitude values ranges from 4.8 m/s^2 to 5.2 m/s^2, respectively, while the tolerance value is equal to ±0.2 m/s^2. Then the modeling of mechanical processes in PCA is carried out with simulation of various defects such as: a weakened PCA fastening (defect No. 1); the absence of ERE (defect No. 2); a crack in PCB (defect No. 3); and a different PCB thickness (defect No. 4). As a result, the amplitude–frequency characteristics (AFC) of vibration acceleration at the PCA control point shown in Fig. 3 are obtained.

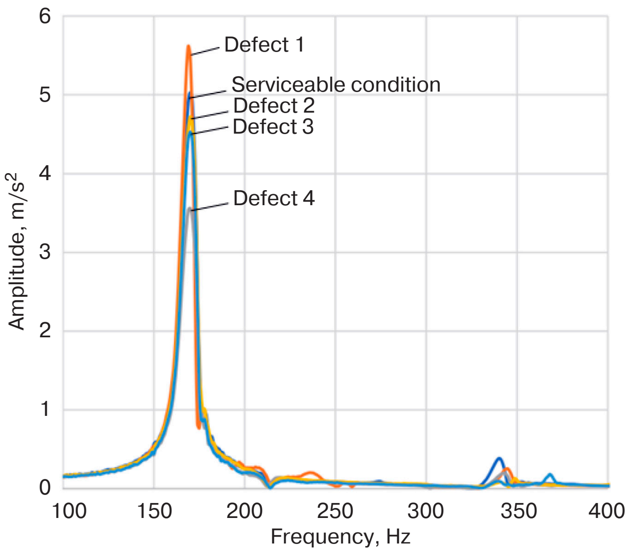


Fig. 3. Calculated values of AFC at the PCA control point in serviceable condition and under different defects

It can be seen from the graphs that each of the defects causes deviation of vibration acceleration AFC at the PCA control point from AFC for the serviceable condition. It is most effective to compare AFC at the first resonant frequency since at other frequencies, the result of comparison may be incorrect. This can be due to small differences in the values of vibration acceleration amplitudes, comparable to the calculation errors.

Further, experimental studies are carried out of the mechanical characteristics of serviceable PCA and PCA with single defects simulated by modeling. The experiment is conducted using a vibration test bench (Fig. 4) at the harmonic vibration frequency equal to the first resonance frequency (170 Hz) obtained as a result of modeling. As a result, the experimental values of vibration acceleration amplitudes at the PCA control point at the resonant frequency under different defects are obtained: for a weakened PCA fastening (defect No. 1), it is 5.6 m/s^2; for the absence of ERE (defect No. 2), it is 4.7 m/s^2; for a crack in PCB (defect No. 3), it is 4.5 m/s^2; and for a different thickness of PCB (defect No. 4), it is 3.5 m/s^2.

Fig. 4. Setup for experimental study of PCA under the impact of harmonic vibration

As seen from the experimental results, each of the defects causes deviation of vibration acceleration values at the PCA control point from the value for the serviceable condition beyond the calculated tolerance obtained as a modeling result. Moreover, a number of defects may cause approximately the same change in vibration acceleration at the PCA control point (for example, defects No. 2 and No. 3 in the experiment) compared to the measurement error. This indicates that it is not possible to determine the type of defect unambiguously (the presence of a particular type of defect can be stated only with a certain degree of probability determined on the basis of the analysis of possible types of defects in the studied REM sample). Consequently, only when comparing the measured values of vibration accelerations with the tolerance limits obtained as a result of simulation modeling, is it possible to draw a conclusion regarding the presence or absence of defects in PCA, and to determine the type of possible defects with a certain probability.

CONCLUSIONS

The method for calculating tolerances for the PCA vibration acceleration amplitude was developed using the Monte Carlo simulation of mechanical processes in REM PCA. This takes into account the spread of physico-mechanical and geometric parameters of REM design. Based on the experimental results, conclusions may be drawn about the legitimacy of applying the described method in calculating permissible values of PCA vibration accelerations in production practice, in order to control the technical condition of REM PCA and search for defects. This method allows the presence of single defects in PCA to be recognized effectively. Studies involving the possible detection of multiple defects (simultaneous presence of two or more defects in PCA) are currently being conducted by the authors of the paper.

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

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About the authors

Vladimir K. Bityukov, Dr. Sci. (Eng.), Professor, Department of Radio Wave Processes and Technologies, Institute of Radio Electronics and Informatics, MIREA – Russian Technological University (78, Vernadskogo pr., Moscow, 119454 Russia). E-mail: bitukov@mirea.ru. ResearcherID Y-8325-2018, Scopus Author ID 6603797260, RSCI SPIN-code 3834-5360, https://orcid.org/0000-0001-6448-8509

Aleksey V. Dolmatov, Cand. Sci. (Eng.), Associate Professor, Department of Design and Production of Radioelectronic Devices, Institute of Radio Electronics and Informatics, MIREA – Russian Technological University (78, Vernadskogo pr., Moscow, 119454 Russia). E-mail: dolmatov@mirea.ru. RSCI SPIN-code 3887-2405, https://orcid.org/0000-0003-2969-2971

Anatoly A. Zadernovsky, Dr. Sci. (Eng.), Head of the Physics Department, Institute for Advanced Technologies and Industrial Programming, MIREA – Russian Technological University (78, Vernadskogo pr., Moscow, 119454 Russia). E-mail: zadernovsky@mirea.ru. ResearcherID B-5463-2016, Scopus Author ID 6602831427, RSCI SPIN-code 2345-7791, https://orcid.org/0000-0002-4017-4836

Anatoly I. Starikovsky, Cand. Sci. (Eng.), Professor, Department of Radio Electronic Systems and Complexes, Institute of Radio Electronics and Informatics, MIREA – Russian Technological University (78, Vernadskogo pr., Moscow, 119454 Russia). E-mail: starikovski@mirea.ru. Scopus Author ID 57208926243, RSCI SPIN-code 1126-4471, https://orcid.org/0000-0003-4040-3843

Ruslan M. Uvaysov, Postgraduate Student, Department of Radio Wave Processes and Technologies, Institute of Radio Electronics and Informatics, MIREA – Russian Technological University (78, Vernadskogo pr., Moscow, 119454 Russia). E-mail: uvajsov@mirea.ru. https://orcid.org/0000-0003-0619-649X

Об авторах

Битюков Владимир Ксенофонтович, д.т.н., профессор, профессор кафедры радиоволновых процессов и технологий Института радиоэлектроники и информатики ФГБОУ ВО «МИРЭА – Российский технологический университет» (119454, Россия, Москва, пр-т Вернадского, д. 78). E-mail: bitukov@mirea.ru. ResearcherID Y-8325-2018, Scopus Author ID 6603797260, SPIN-код РИНЦ 3834-5360, https://orcid.org/0000-0001-6448-8509

Долматов Алексей Вячеславович, к.т.н., доцент, кафедра конструирования и производства радиоэлектронных средств Института радиоэлектроники и информатики ФГБОУ ВО «МИРЭА – Российский технологический университет» (119454, Россия, Москва, пр-т Вернадского, д. 78). E-mail: dolmatov@mirea.ru. SPIN-код РИНЦ 3887-2405, https://orcid.org/0000-0003-2969-2971

Задерновский Анатолий Андреевич, д.т.н. заведующий кафедрой физики Института перспективных технологий и индустриального программирования ФГБОУ ВО «МИРЭА – Российский технологический университет» (119454, Россия, Москва, пр-т Вернадского, д. 78). E-mail: zadernovsky@mirea.ru. ResearcherID B-5463-2016, Scopus Author ID 6602831427, SPIN-код РИНЦ 2345-7791, https://orcid.org/0000-0002-4017-4836

Стариковский Анатолий Иванович, к.т.н., профессор, кафедра радиоэлектронных систем и комплексов Института радиоэлектроники и информатики ФГБОУ ВО «МИРЭА – Российский технологический университет» (119454, Россия, Москва, пр-т Вернадского, д. 78). E-mail: starikovski@mirea.ru. Scopus Author ID 57208926243, SPIN-код РИНЦ 1126-4471, https://orcid.org/0000-0003-4040-3843

Увайсов Руслан Магомедович, аспирант, кафедра радиоволновых процессов и технологий Института радиоэлектроники и информатики ФГБОУ ВО «МИРЭА – Российский технологический университет» (119454, Россия, Москва, пр-т Вернадского, д. 78). E-mail: uvajsov@mirea.ru. https://orcid.org/0000-0003-0619-649X

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