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Analysis of the physical foundations of the build quality of the diagnosis structures based on electronic means of recording and analyzing the parameters of electromagnetic radiation mechanical contact connections

Abstract. *The paper presents the results of research that can be put into the development and research of non-contact rapid method for assessing the quality of the assembly and installation of EM designs. To achieve the objectives, studied the behavior of the mechanical connection of the contact pairs, namely the definition of the contribution of R,L,C parameters contact joints in the modulation level and the spectral composition of the electromagnetic radiation mechanical contact pair*

Streszczenie. *W artykule przedstawiono wyniki badań, które mogą być wprowadzane do rozwoju oraz badań bezdotykowego szybkiego sposobu oceny jakości montażu i instalacji projektów EM. W tym celu zbadano zachowanie połączenia mechanicznego pary styków, mianowicie zdefiniowano wpływ parametrów R, L, C połączeń stykowych na poziom modulacji i skład widmowy promieniowania elektromagnetycznego mechanicznego styku par.* ***(Analiza fizycznych podstaw jakości wykonania struktur diagnostycznych opartych na elektronicznym sposobie rejestrowania i analizowania parametrów promieniowania elektromagnetycznego mechanicznych połączeń stykowych)***

Keywords: diagnostics, mechanical connections, electromagnetic radiation, interference contact
Słowa kluczowe: diagnostyka, połączenia mechaniczne, promieniowanie elektromagnetyczne, styk

Introduction

In today's design and manufacture of electronic means (EM) for assessing the quality of produced mechanical constructions, comprising testing the level of structural strength parameters are used, usually different types of mechanical influences. In this case, removed from the EM signal via mechanical quantities sensors that contain diagnostic information, it is concluded that the technical condition of the structure, the presence of defects. Among the main parameters that characterize the quality of assembly is the presence of non-compliance with tightening torques of threaded connections. This analysis is associated with the processing of large volumes of data on the characteristics of the measured vibration signals and does not provide unambiguous information on the availability and location of defects in the structure. Therefore, the creation of simple and reliable EM diagnostics express methods is urgent. The investigations can be put into the development and research of non-contact rapid method for assessing the quality of the assembly and installation of designs. The method is based on the registration and analysis of artificially excited by contact noise when exposed to mechanical vibrations and harmonic electric high frequency signal on structural elements EM forming circuit phase-amplitude-modulated oscillations which are registered spectrum analyzer or receiver FAM or AM hesitation. At the same time, measure the levels of its spectral components as the frequency of mechanical influences in the range determined by operating conditions. Measured spectral components emitted by amplitude-modulated waves is compared with the level of the spectral components of the signal emitted by the reference block design with desired mechanical parameters and having a normalized level of contact interference. Considered in the field of electromagnetic compatibility (EMC) as an undesirable phenomenon, the formation of contact interference can be used to evaluate the mechanical properties of a wide variety of designs and hardware devices, including the quality of assembly and installation (especially related to the effort of tightening fasteners).

Object of study

The proposed method can be used to determine the mechanical resonance frequency in the structures of electronic equipment. The maximum measured levels of spectral components at frequencies changing mechanical effects, allow you to set the values of the resonance frequencies in structures [1]. In the modern production of electronic structures (EM) to assess the quality of manufactured products designs use different methods for evaluating the quality of structural assemblies, using various kinds of mechanical influences on the design by which assess the quality of the assembly and installation work. Electric Mechanical tests reveal the presence of defects in design, to assess the impact of structural factors on the EM quality parameters. check that the parameters of the requirements specification equipment. Known methods for assessing the quality of assembly structures EM units. consists in carrying out mechanical tests on vibration strength, wind resistance, impact resistance, does not reveal defects in the EM structures and adequately assess the quality of the assembly and installation work. Determination of particle resonance oscillation amplitudes, and the maximum mechanical stress in structural elements is not possible to evaluate the product build quality, especially at the sites of attachment, where there are normalized values puffs fasteners deformation at the junction of the individual parts. Existing sensors for measuring the amplitudes and accelerations do not allow to assess the movement of jointed parts in designs. Electrical contacts are an important part of the electrical and mechanical design of electronic equipment. The conditions at which the operation of electrical contacts, have a serious impact on the parameters of the latter. Such conditions include the following external influencing factors: electrical, thermal, mechanical, climatic. An example, is characterized by significant mechanical stress, it is movable objects which are placed on-board radio-electronic means, containing a large number of interconnected metal elements forming the system of electrical contacts.

Some of them are due to the rigid and reliable connection elements are fixed, others when driving, especially in the case of non-rigid connection elements of the object are variables. One important task is to study the characteristics of the electrical contacts under the influence of mechanical factors.

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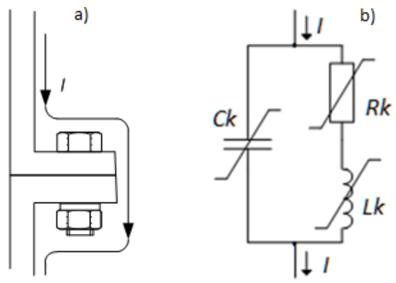

Fig. 1. Bolting (a) and the equivalent parametric variable impedance circuit contact (b)

In the absence of mechanical external influences on connected structural elements occurs in a stable contact time between these elements, which allows the emission of radio transmitting equipment to consider the case and the individual elements of structures as the conductive body, placed in a high-frequency electromagnetic field. The exact calculation of the value of EMF induced by irradiating the electromagnetic field on the conductors of arbitrary configuration is a complex problem [2]. The flow of current in the exposed conductors is accompanied by the emergence of the secondary electromagnetic field having the same spectral structure as irradiating the electromagnetic field, but differs from it in amplitude and phase. Interaction secondary radiating electromagnetic fields and distorts the overall structure of the electromagnetic field near the metallic surface of the object, but no additional spectral components do not occur in this case. Under the influence of an external electromagnetic field irradiating on the contact pair (Fig. 1a) at an equivalent conductor (contact pair) bring EDS to the spectral structure of the radiating field. Assume that the transmitter emits narrowband signal formed by modulating a harmonic signal amplitude and phase. Then, the voltage induced in the equivalent of a conductor can be written as

$$\dot{U}(t) = U(t)\cos\left[\omega_o t + \Phi(t) + \varphi_o\right] \quad (1)$$

where: $\dot{U}(t)$ - the amplitude of the voltage, which is determined by the law of amplitude modulation of the irradiating electromagnetic field, ω_0 - circular frequency of the illuminating electromagnetic field, $\Phi(t)$ - the law of phase modulation, φ_0 - the initial phase.

The magnitude of the conduction current in the equivalent conductor can be calculated by the formula

$$i_k(t) = \frac{u(t)}{\mathrm{Z}(t)} = u(t)\,y(t) \quad (2)$$

where: $y(t)=1/Z(t)$ conductivity equivalent conductor We write $u(t)$ and $y(t)$ in complex form

$$u(t) = \mathrm{Re}\left\{U(t)e^{j(\omega_0 + y(t)\varphi_0}\right\},\ y(t) = \mathrm{Re}\left\{Y(t)e^{j\varphi(t)}\right\} \quad (3)$$

where: $U(t) = U(t)\ e^{j\varphi(t)}$

Integrated voltage envelope, which lies about a modulated signal transmitted by irradiating an electromagnetic field. Then, the conduction current in the equivalent conductor can be written as

$$\begin{aligned} i_k(t) &= \mathrm{Re}\left\{U(t)Y(t)e^{j\varphi(t)}e^{j(\omega_0 t+\varphi_0}\right\} = \\ &U(t)Y(t)\cos\left[\omega_0 t + \phi(t) + \varphi_0 + \varphi(t)\right] \end{aligned} \quad (4)$$

From this expression, it follows that the current range is different from the spectrum of the irradiating electromagnetic field. It contains additional spectral components of a change in the contact resistance. In this situation occure amplitude and phase distortion, and hence the secondary alternating electromagnetic field exposure of radiation to be materially different from the spectral structure of the original illuminating field.

Based on the above, clearly leads to the conclusion that registration of the spectral components resulting from the re-emission, can serve as parameters characterizing the state of the contact resistance, or in other words, the parameters characterizing the quality of the design elements of the assembly (Fig. 2). Another embodiment of the study may be the task of registering the signal spectrum with phase-amplitude modulation of the emitting structure of ES and its components, in which the emission spectrum analysis is carried out design and its elements. When this structure is included in the high radiation generator circuit. Spectrum analysis and the measurement of the modulation signal parameters by using FAM signal receivers (Fig. 2b).

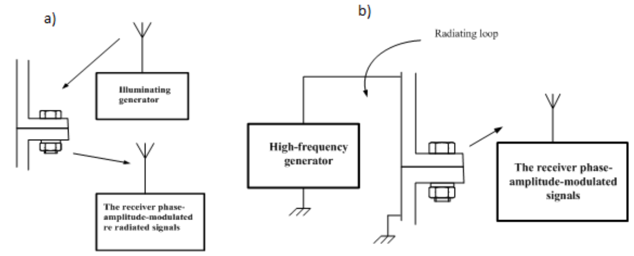

Fig. 2. Methods of obtaining information about the build quality: a - registration of the information about the parameters of re-emission signal; b - Check information about the parameters of the radiation signal

Metod of research

To achieve the objectives, a priority task is to study the behavior of the mechanical connection of the contact pairs, namely the definition of the contribution of R, L, C parameters in the modulation level and the spectral composition of the electromagnetic radiation contact pair [3-5]. Fig. 1a shows a fragment of a bolted joint designs, typical of many moving objects. Under the influence of mechanical factors on the compound (shaking, vibration, shock, acoustic noise) electrical contact formed structures will change their electrical parameters. Fig. 1b shows the equivalent parametric circuit impedance electrical contact for high-frequency signal transmitted by the action of mechanical stress on the contact. Full transition electric contact resistance in the static state is equal to

(5)
$$\dot{Z}_к(\omega, R_K, L_K, C_K) = \frac{R_к}{(1-\omega^2 C_к L_к)^2 + \omega^2 R_к^2 C_к^2} + j\frac{\omega L_к(1-\omega^2 L_к C_к) - \omega R_к^2 C_к}{(1-\omega^2 C_к L_к)^2 + \omega^2 R_к^2 C_к^2}$$

where: R_K - resistivity of the contact transition; L_K - inductance of the contact transition, C_K - capacity contact transition.

In the future, we omit the index "k" when the resistivity, inductance and capacitance electrical contact realizing that we are talking about the contact settings. From (5) it follows that the total contact resistance is a complex frequency-dependent quantity and is characterized by amplitude and phase parameters of the [4, 5].

From Figure 1b it follows that the electrical contact is an electrical circuit for which at certain frequencies passing electrical signal response current characteristic. This phenomenon is characterized by the fact that the current transfer ratio of each of the branches (inductive and capacitive) may be greater than one. Consider the amplitude and phase characteristics of the electric contact transfer coefficients. By definition, in the inductive branch current transfer ratio is equal to

(6)
$$\dot{K}_L = \frac{\dot{I}_L}{\dot{I}} = \frac{\dot{Z}_K}{\dot{Z}_L} = \frac{\dot{Z}_K}{j\omega L_K + R_K}$$

where: $\dot{I}$ - current in the straight part of the chain; $\dot{I}_L$ - current in the inductive branch.

After arithmetic conversions complete model of the current transfer ratio in the inductive branch is

(7)
$$\dot{K}_L(\omega, R, L, C) = \frac{R^2 + (\omega L)^2 - \omega^2 R^2 CL - \omega^4 CL^3 + j(-\omega CR^3 - \omega^3 CL^2 R)}{((1-\omega^2 C_к L_к)^2 + \omega^2 R_к^2 C_к^2)\cdot(R^2 + (\omega L)^2)}$$

Fig. 3 show the amplitude-phase characteristics of a current gain in the inductive branch, i.e. dependence of the modulus and phase of the transmission coefficient of the frequency. Graphs are shown for the following parameters of the electrical contact $R = 10^{-3}\Omega$, $L = 8\cdot10^{-11}$ Gn, $C = 3.10^{-10}F$. The frequency of the signal transmitted is seen in the range of 2π·(0,3 ÷ 30)·10^6Hz. The graphs show that the resonant frequency of contact under these conditions is much higher than the considered range. For these conditions it is equal to 5.8·10^9 Hz. Nevertheless, a change in the amplitude and phase of the current gain occurs. When $\omega=0$, the module gain equal to unity, since in this case the entire current will pass through the resistive branch. With increasing frequency gain module increases. During the frequency range it increased by 0.1%.

When $\omega=0$, the phase is zero transmission coefficient, as in this case, a purely resistive branch. With increasing frequency, the phase of the transmission coefficient decreases. During the frequency range is reduced by 0.4%.

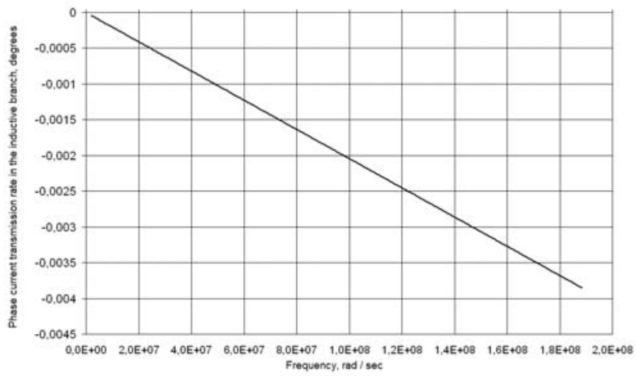

Fig. 3. Dependence of the phase current transfer ratio in the inductive branch of the signal frequency

By definition, a capacitive branch current transfer ratio is equal to

(8)
$$\dot{K}_C = \frac{\dot{I}_C}{\dot{I}} = \frac{\dot{Z}_K}{\dot{Z}_C} = \frac{-\dot{Z}_K \omega C_K}{j}$$

After arithmetic conversions complete model of the current transfer ratio in the capacitive branch is

(9)
$$\dot{K}_C(\omega, R, L, C) = \frac{\omega^4 C^2 L^2 + \omega^2 C^2 R^2 - \omega^2 LC + j\omega CR}{(1-\omega^2 C_к L_к)^2 + \omega^2 R_к^2 C_к^2}$$

Fig. 4 and 5 show the amplitude-phase characteristics of a current gain in the capacitive branch. Graphs are shown for the electrical contact of the same parameters as in the case of an inductive branch. When $\omega=0$, the module transmission ratio is zero because in this case the entire current will pass through the resistive branch. With increasing frequency gain module increases. During the frequency range it increased by 0.1%.

At $\omega=0$ the phase of the transmission coefficient tends to zero. With increasing frequency the phase of the transmission coefficient increases significantly. During the frequency range is increased by 78%

Let us now consider the dynamic behavior of the current transfer ratios. To do this, use the formulas connection resistivity, inductance and capacitance electrical contact from the contact force. For resistivity, it has the form

(10)
$$R_K = c\rho\frac{\sqrt{H}}{P_K^b}$$

where: c - coefficient depending on the method, surface finish and surface condition, ρ - conductivity of the contact material, H - surface Brinell hardness, P_K^b - contact force, *b*- the exponent, depending on the nature of the deformation, the type and shape of contact area.

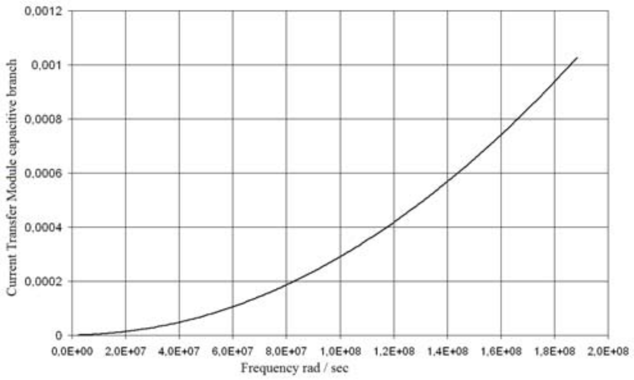

Fig. 4. Dependence of the gain module current in the capacitive branch of the signal frequency

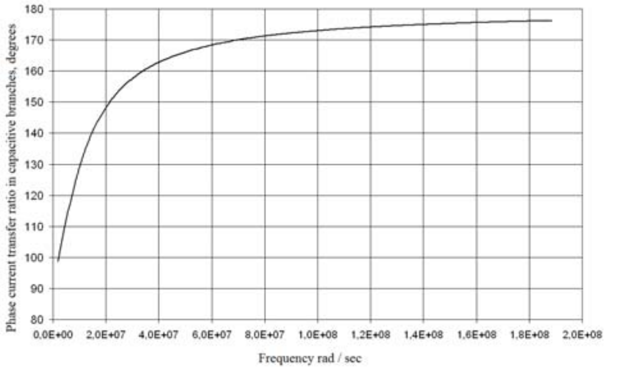

Fig. 5. Dependence of the phase current transfer ratio in the capacitive branch of the signal frequency

The inductance of the transition zone of contact is

(11) $$L_K = \mu(1,545(D-2a) - 0,533D)\cdot 10^{-7}$$

where: μ - relative permeability of the contact material, D - the apparent diameter of the contact surface, a - the radius of the contact area.

The capacity of the transition zone of contact without the presence of the film is

(12) $$C_K = 5,5\cdot 10^{-11}\ln(r/2a)$$

where r - radius of the top of unevenness, a - the radius of the contact area.

To calculate the radius of the contact area of the contact force will use the Hertz formula for contacting the two areas in the theory of elasticity:

(13) $$a(P_K) = 0,00872\sqrt[3]{\frac{P_K}{10}\left(\frac{\frac{10^{-5}}{E_1}+\frac{10^{-5}}{E_2}}{\frac{1}{100r_1}+\frac{1}{100r_2}}\right)}$$

where: P_K - contact force, E_1 and E_2 - elastic contacting materials modules, r_1 and r_2 - contacting the radii of the spheres.

When changing the contact force of the $P_{K1}=10N$ to $P_{K2}=90N$ primary electrical contact parameters calculated by the above formulas will be equal to: $R_{K1}=38,09\cdot 10^{-3}\Omega$, $R_{K2}=19,7\cdot 10^{-3}\Omega$, $L_{K1}=8,095\cdot 10^{-11}Gn$, $L_{K1}=8,094\cdot 10^{-11}Gn$; $C_{K1}=4.38\cdot 10^{-10}F$, $C_{K2}=3.98\cdot 10^{-10}F$. The above calculations show that with this rather significant change in scope of the contact force the most significant change is characteristic of the resistivity of the electrical contact. Consider the effect on the resistivity of the current transmission ratios in both branches. To do this, we first find an expression for the absolute sensitivity of the functions of the current transfer ratios.

By definition, the absolute function of the sensitivity of the output characteristics of the parameter is equal to

$$A^{y}_{q^r} = \frac{1}{r!}\left(\frac{\partial^p y}{\partial^r q}\right)_{q_0}$$

(14)

where: y - output characteristic, p - order partial derivative of the output function, q - sensitivity setting, r - order partial derivative of the sensitivity parameter, q_0 - vector design parameters values for which the calculated partial derivative.

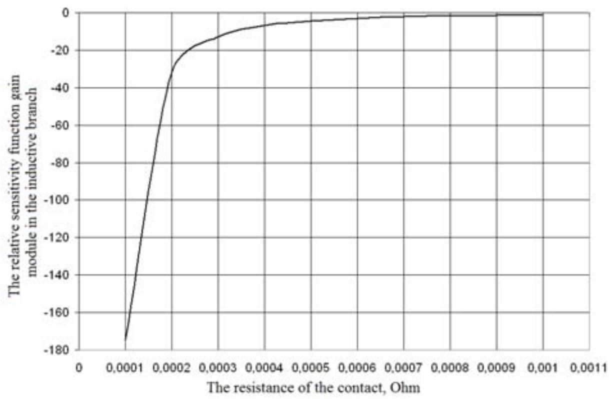

Fig. 6. Relative sensitivity function gain module current in the inductive branch of the value of active contact resistance

For the absolute sensitivity of the function module for the current transfer ratio in the inductive branch of the resistive electrical contact following calculation model is obtained

(15)

$$A^{K_L}_{R}(\omega, R, L, C) =$$

$$\frac{1}{2\cdot\sqrt{\left[\frac{(C^2+\omega^2R^2-\omega^2C^2LR-\omega^4LR^3)^2}{((\omega LC)^2+(\omega^2LR-1)^2)^2\cdot(C^2+\omega^2R^2)^2}+\frac{[(-\omega)LC^3-\omega^3LR^2C]^2}{((\omega LC)^2+(\omega^2LR-1)^2)^2\cdot(C^2+\omega^2R^2)^2}\right]}}\times$$

$$\times\left[\frac{1}{((\omega LC)^2+(\omega^2LR-1)^2)^2\cdot(C^2+\omega^2R^2)^2}\right]\cdot[2(C^2+\omega^2R^2-\omega^2C^2LR-\omega^4LR^3)\times$$

$$\times(2\omega R^2-2\omega C^2LR-4\omega^3LR^3)-\frac{2(C^2+\omega^2R^2-\omega^2C^2LR-\omega^4LR^3)^2(2\omega^4L^2R-2\omega^2L)}{(\omega LC)^2+(\omega^2LR-1)^2}-$$

$$-\frac{4(C^2+\omega^2R^2-\omega^2C^2LR-\omega^4LR^3)^2\omega^2R}{(C^2+\omega^2R^2)}-4((-\omega)LC^3-\omega^3LR^2C)(\omega^3LRC)-$$

$$-\frac{2((-\omega)LC^3-\omega^3LR^2C)^2(2\omega^4L^2R-2\omega^2L)}{(\omega LC)^2+(\omega^2LR-1)^2}-\frac{4((-\omega)LC^3-\omega^3LR^2C)^2\omega^2R}{(C^2+\omega^2R^2)}]$$

For the absolute functions in the inductive branch of the sensitivity of the phase of the current transfer ratio of the resistivity of the electrical contact obtained next calculation model

(16):

$$A^{\phi_{K_L}}_{R}(\omega, R, L, C) =$$

$$\frac{(-2)\omega^3LR\dfrac{C}{C^2+\omega^2R^2-\omega^2C^2LR-\omega^4LR^3}-\dfrac{(-\omega)LC^3-\omega^3LR^2C}{(C^2+\omega^2R^2-\omega^2C^2LR-\omega^4LR^3)^2}\cdot(2\omega^2R-\omega^2C^2L-3\omega^4LR^2)}{1+\dfrac{((-\omega)LC^3-\omega^3LR^2C)^2}{(C^2+\omega^2R^2-\omega^2C^2LR-\omega^4LR^3)^2}}$$

For comparison, the influence of individual parameters on the same output characteristic using the relative sensitivity function which is equal to:

(17) $$S_{q^r}^{y} = A_{q^r}^{y}\frac{q_0^r}{y_0}$$

where $A_{q^r}^{y}$ - the absolute sensitivity function, q_0^r - vector of the calculated values of parameters for which the calculated partial derivative of r-th order, y_0 - the values of the output characteristics at.

Fig. 7 and 8 shows the dependence of the relative sensitivity of the functions of the module and the phase of the transmission coefficient of the current in the inductive branch. Graphs are shown when changing the contact resistivity of 10^{-4} to 10^{-3} Ω. From these curves shows significant effect on contact changes its resistivity in the inductive branch of the current transmission rate as in modulus and phase.

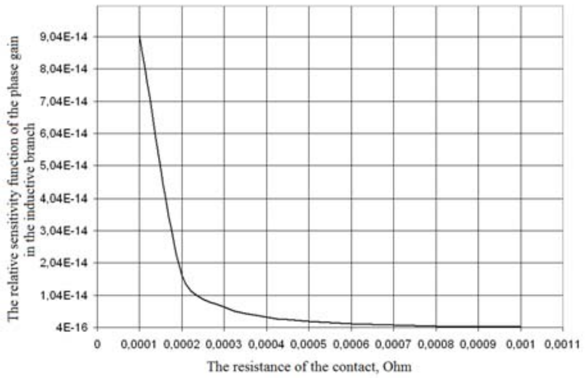

Fig. 7. Relative sensitivity function phase current transfer ratio in the inductive branch of the value of active contact resistance.

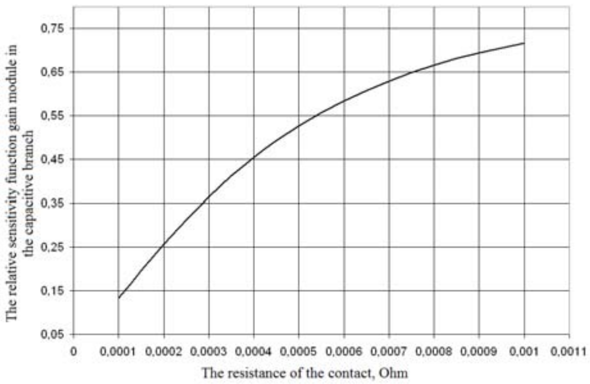

Fig. 8. Relative sensitivity function gain module from the current value of the active contact resistance

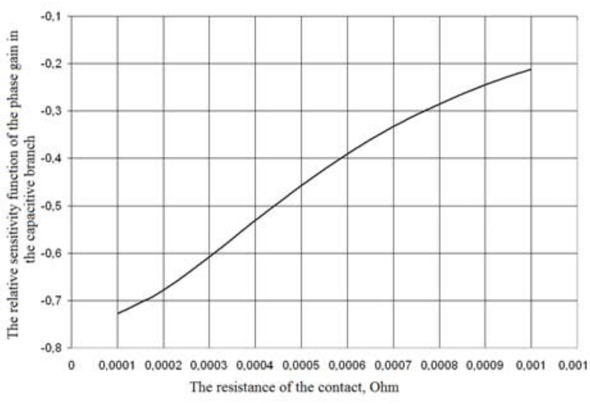

Fig. 9. Relative sensitivity function phase current transfer ratio in the capacitive branch of the value of active contact resistance

For the absolute sensitivity function gain module current in the capacitive branch of the resistive electrical contact following calculation model is obtained:

(18)

$$A_R^{K_C}(\omega,R,L,C)=$$

$$\frac{1}{2\sqrt{\left[\frac{(\omega^4C^2L^2+\omega^2C^2R^2-\omega^2LC)^2}{((\omega^2CL-1)^2+(\omega CR)^2)^2}+\frac{(\omega CR)^2}{((\omega^2CL-1)^2+(\omega CR)^2)^2}\right]}}\cdot$$

$$\left[\frac{1}{((\omega^2CL-1)^2+(\omega CR)^2)^2}\right]\times$$

$$\times[4(\omega^4C^2L^2+\omega^2C^2R^2-\omega^2LC)\omega^2C^2R-$$

$$4\frac{(\omega^4C^2L^2+\omega^2C^2R^2-\omega^2LC)^2\omega^2C^2R}{(\omega^2CL-1)^2+(\omega CR)^2}+2\omega^2C^2R$$

$$-4\frac{\omega^4C^4R^3}{(\omega^2CL-1)^2+(\omega CR)^2}]$$

For absolute capacitive branches function in sensitivity phase current transfer ratio of the resistivity of the electrical contact obtained next calculation model:

(19)

$$A_R^{\varphi_{K_C}}(\omega,R,L,C)=$$

$$\frac{\omega\frac{C}{\omega^4C^2L^2+\omega^2C^2R^2-\omega^2LC}-2\omega^3C^3\frac{R^2}{(\omega^4C^2L^2+\omega^2C^2R^2-\omega^2LC)^2}}{1+\frac{\omega^2C^2R^2}{(\omega^4C^2L^2+\omega^2C^2R^2-\omega^2LC)^2}}$$

Fig. 7 and 8 shows the dependence of the relative sensitivity of the functions of the module and the phase of the transmission coefficient of the current in the capacitive branch. Graphs are shown when changing the contact resistivity of 10^{-4} to 10^{-3} Ω. From these curves shows significant effect changes its contact resistivity in the capacitive branch current transfer ratio as in modulus and phase.

Overall transmission ratio of the current of electrical contact is the vector sum of the transfer coefficients for the current in the inductive and capacitive branches:

(20) $$\dot{K}(\omega,R,L,C)=\dot{K}_L(\omega,R,L,C)+\dot{K}_C(\omega,R,L,C)$$

Under static conditions, the full current transfer ratio is equal to one, ie, passing current does not experience changes in amplitude and phase (excluding heat loss). The dynamics is changing the primary electrical contact parameters that affect the flowing current in amplitude and phase. For example, when changing the contact force of the $P_{K1}=10N$ to $P_{K2}=90N$ in the inductive branch coefficient of current transfer varies from module $K_{L1}=1,000139$ to $K_{L2}=1,000127$, the phase of $\varphi K_{L1} = -0,06$ degrees to φK_{L2}=-0.02 degrees. Current Transfer Ratio in the inductive branch under the same conditions, changes in modulus of $K_{C1} = 1.058\cdot10^{-3}$ *to* $K_{C2} = 5.091\cdot10^{-4}$, the phase of $\varphi K_{C1} = 97.54$ degrees to $\varphi K_{C2} = 104.44$ degrees. It should be noted that in the capacitive branch update module current transmission rate an order of magnitude change in gain module current in the inductive branch and a capacitive branch of the phase change current transmission factor of four orders of magnitude change in the phase current transmission rate in the inductive branch. The dynamics of change in the total electrical contact transmission rate will be equal to

$$\Delta\dot{K}(\omega, R, L, C) = (|\dot{K}_{L1}| - |\dot{K}_{L2}|) \cdot e^{j(\phi_{KL1}-\phi_{KL2})} + (|\dot{K}_{C1}| - |\dot{K}_{C2}|) \cdot e^{j(\phi_{KC1}-\phi_{KC2})} \quad (20)$$

where $|\dot{K}_{L1}|$ and $|\dot{K}_{L2}|$, $\phi_{KL1} - \phi_{KL2}$ - the modules and phases of the current transmission rate in the inductive branch at different points in time t_1 and t_2; $|\dot{K}_{C1}|$ and $|\dot{K}_{C2}|$, ϕ_{KC1} and ϕ_{KC2} - the modules and the phase-current transmission factor in the capacitive branch at different points in time t_1 and t_2. For this example to change the module complete current transfer ratio is equal to $5.62 \cdot 10^{-4}$, and the phase change of 6,74 degrees.

Rezalt and discussion

Thus, when a periodic action of mechanical force to the electrical contact will occur periodically varies the current gain in the amplitude and phase, i.e. amplitude and phase modulation of passing an electric current will occur. By recording and analyzing the spectral composition of light elements mechanically connected to EM design can monitor the quality of the assembly of structural elements. Through a comprehensive diagnosis based on the measurement of the spectral composition of the whole product, positioning measuring antenna around the investigational product can make reliable estimates of build quality as the individual mechanical components, and the whole structure of EM as a whole.

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