Design of Radio-Electronic Means Taking into Account Electromagnetic, Thermal and Mechanical Characteristics

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Abstract. The article discusses an integrated approach to the process of assembling the blocks and cells of the radio electronic means (REM), taking into account the electromagnetic, thermal and mechanical characteristics. A technique is proposed for the optimal layout of the REM structure based on the use of 3D models. A practical application of the technique for solving a production problem is presented, which has shown qualitative improvements in the technical and operational parameters of the product - the temperature of the most heat-loaded element, the maximum temperature inside the case, the strength of the electromagnetic and electric fields and the noise immunity of the structure. The description of the methodology for evaluating the electromagnetic characteristics of printing board (PB) in closed structures is presented.

Keywords: Radio electronic means, Thermal conditions, Optimization, Electromagnetic compatibility.

1 Introduction

In modern industrial conditions, computer modeling systems are the main tool for developers of REM. Namely, the entire process of developing modern electronic equipment is carried out in specialized computer-aided design systems (CAD). However, the constant increase in the complexity and density of the layout leads to an increase in the requirements for the qualifications of developers, an increase in the cost of designing and testing electronic equipment, and a slowdown in the process of creating promising devices. The development of special thermal protection means and the creation of methods for ensuring electromagnetic compatibility (EMC) and noise immunity (NI) of REM units located in an isolated space, the creation of new types of cooling systems (CO) that meet specific requirements, improving their energy and technical and economic indicators is an important task [1]. The functioning, reliability and control of devices in the immediate vicinity depends significantly on the efficiency of the temperature control systems and their operation. As a rule, the operation of such devices and devices is associated with the need to remove high heat flux densities [2].

It is customary to distinguish the following EMC levels: intersystem, intrasystem and intra-hardware. And if on the first two levels there is a sufficiently large number of scientific and applied works that make it possible to effectively solve emerging problems, then in-hardware EMC and NI is the area that has not been given due attention until now. And as a result, in the existing production processes, these issues of ensuring the requirements for EMC and NI during the development of REM were assigned a secondary role. But at the moment, the border has been reached when a further increase in the efficiency of the development of radio electronic devices is possible only taking into account the requirements of EMC and NI and solving problems to ensure them [3].

Thus, an urgent problem arises of creating and subsequent improvement of methods for the optimal arrangement of cells and blocks of REM, taking into account the electromagnetic, thermal and mechanical characteristics, adapted to the existing production conditions.

2 Development of a methodology for the layout of rem units taking into account electromagnetic and thermal characteristics

A technique has been developed for the optimal layout of the REM units, taking into account the electromagnetic and thermal characteristics.

The proposed technique includes the following sequence of actions:

1. The analysis of the initial data and requirements for the final design is carried out.
2. All necessary 3D models are created.
3. The initial layout of the unit is made, taking into account the requirements and limitations in terms of EMC and thermal conditions.
4. At this stage, it is required to adapt the 3D models for further analysis of the thermal regime.
5. It is required to simulate the thermal regime of the block.
6. At this stage, a choice is made based on the previously obtained result of the analysis, the need to use CO.
7. If it is necessary to use CO, it is selected.
8. The calculation of the thermal regime is carried out using a specialized CAD system, taking into account the CO used.
9. After carrying out the simulation and with the results satisfying the requirement for the thermal regime, you should go to the eleventh point.
10. If the results do not satisfy the requirements for the thermal regime, it is decided whether the choice of another CO will help or it is required to re-arrange the block and the assembly units included in it.
11. At this stage, it is required to adapt the 3D models to the analysis of the electromagnetic environment.
12. The EMC of the unit is analyzed.

13. A choice should be made based on the result of the analysis, whether the installation of the screen is required or not.

14. At this stage, you need to select a screen, if it is required by the results of the primary simulation.

15. An EMC analysis is performed with the shield installed.

16. After the analysis and with the results satisfying the EMC requirement, go to the eighteenth point.

17. If the results do not meet the EMC requirements, it should be decided whether the selection of a different shield will help or whether the unit and its sub-assemblies need to be rearranged.

18. If changes have been made to the design of the unit, then a final analysis should be carried out to ensure that the technical specifications in the field of temperature and EMC are met. If there are no changes made in this iteration, the algorithm will be considered complete.

In Fig. 1 shows the procedure for creating a 3D model. To create a model, you need:

1. Get a 3D model of the board from the designer who developed it.
2. Create a body with dimensions corresponding to the mating parts and assembly products, and the requirements of the technical assignment.
3. Create mounting holes and fittings for elements.
4. Create the mating body and all auxiliary parts.

In Fig. 2 shows the procedure for the preliminary layout of the REM unit. At this stage, the assembly of the unit is performed taking into account the requirements and restrictions in the technical task in terms of EMC and thermal conditions, with subsequent correction, if necessary, of parts due to changes in the installation and overall dimensions.

When locating components, you should rely on the following:

1. Components requiring special locations, for example, controls, must be strictly tied to the specified locations.
2. Install nearby elements that have a large number of reciprocal relationships.
3. Place heat-loaded elements closer to cooling systems and away from heat-sensitive elements.
4. Do not place interference-sensitive components near components that may cause interference.

A distinctive feature of the analysis of heat transfer processes carried out during design is the need to consider the process of the same physical nature for the entire device or complex. The complete mathematical model of the thermal regime of the device is written in the form of a system of multidimensional non-stationary equations of heat conductivity for solids (1) and energy equations for coolant fluxes (2) with boundary conditions 1, 2, 3 kinds or with conjugation conditions at the interfaces of elements.

$$c_i \rho_i \frac{\delta T_i}{\delta \tau} = \nabla\left(\lambda_i \nabla T_i\right) + q_{vi}, \tag{1}$$

where i = 1,...,I; I is the number of bodies; T_i - temperatures of solids; τ is time; c_i - specific heat capacities of bodies; ρ_i - density of solids; q_{vi} - volumetric heat flux densities.

$$c_l \rho_l \left(\frac{\delta \upsilon_l}{\delta \tau} + \vec{\upsilon} \nabla U_i \right) = \nabla \left(\lambda_i \nabla U_i \right), \tag{2}$$

where i = 1,...,L; U_i - temperatures of heat carriers; υ is the speed of movement of the coolant; L is the number of coolant flows [4].

The mathematical model for electromagnetic analysis can be considered the model of current radiation in the differential mode.

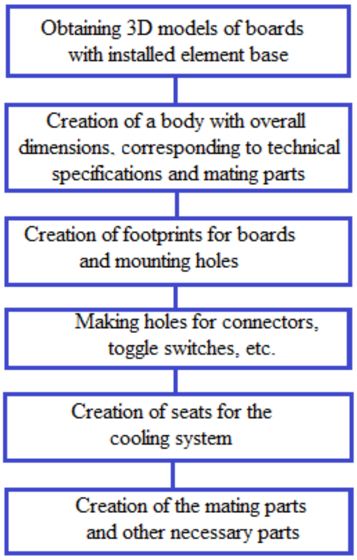


Fig. 1. Procedure for creating a 3D block model.

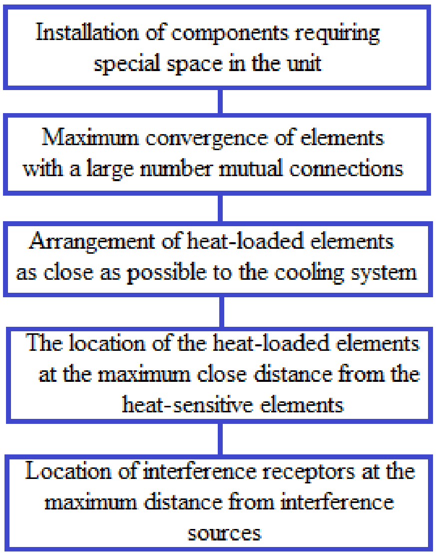


Fig. 2. The procedure for assembling the REM unit.

For a measured distance of 3 m, the maximum conductor length must be no more than one meter. The assumption of a constant distribution of currents in the conductors is an acceptable approximation, provided that the conductors are electrically short at the frequency of interest to us. This greatly simplifies the results and is used in many practical problems. For example, a 0,5 m trace is equal to the free-space wavelength at 600 MHz. The same conductor at a frequency of 100 MHz will be six times shorter than the wavelength, and the distribution of currents along it is approximately constant.

The radiated fields can be determined by assuming a constant distribution of currents in the conductors, taking each wire as a Hertz dipole. As a result, the maximum electric field strength for the differential mode will be determined

$$E_{\max} = 1{,}316 \cdot 10^{-14} \frac{f^2 \cdot i \cdot l \cdot s}{d}, \frac{V}{m} \tag{3}$$

where i - is the current of transmission lines in differential mode, A; f - is the frequency of interest, Hz; l - is the length of the device segment, m; s - distance between conductors, m; d - is the distance between the center of the set of conductors and the location of the measuring antenna, m.

The direction of the electric field strength vector will be parallel to the conductors [5].

On the basis of the above methodology for the arrangement of REM units, taking into account the thermal and electromagnetic parameters, the unit of the microwave amplifier was optimized.

The optimization of the microwave amplifier unit was carried out using a modern CAD system:

1) 3D models creation and block layout in Creo Parametric;

2) modeling of thermal processes in Autodesk Simulation CFD;

3) simulation of electromagnetic interference in CST Studio Suiet.

The unit is part of the radio station.

The product is intended for use in structures:

- maximum elevated temperature of the environment - up to 30°C;
- limiting low temperature of the environment - from 5°C;
- operating frequency range 300-600 MHz;
- working relative humidity of air no more than 80% at a temperature of 25°C;

Supply voltage - 12 V;

Efficiency - 0,7.

The power amplifier unit (Fig. 3) consists of an amplifier cell and a filtering cell (shown in Fig. 4).

A preliminary analysis gave the following results, shown in Fig. 5 and Fig. 6.

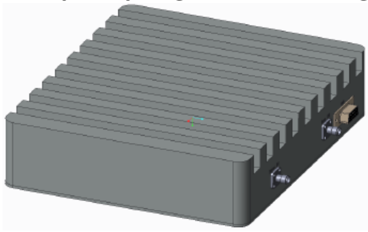


Fig. 3. Exterior view of the investigated block.

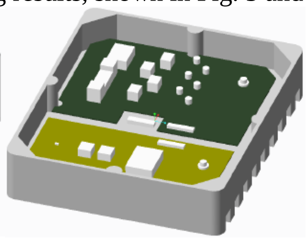


Fig. 4. Adapted 3D block model for analysis.

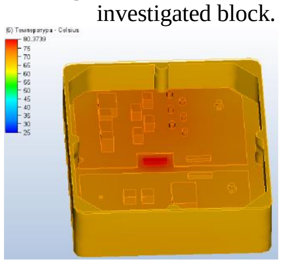


Fig. 5. The result of a preliminary analysis of the thermal regime.

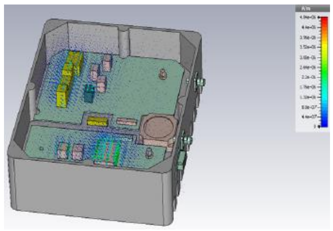


Fig. 6. The result of a preliminary analysis of the magnetic field strength.

After performing the optimization using the proposed methodology for the layout of the REM units, taking into account the electromagnetic and thermal characteristics, the results shown in Fig. 7 and Fig. 8.

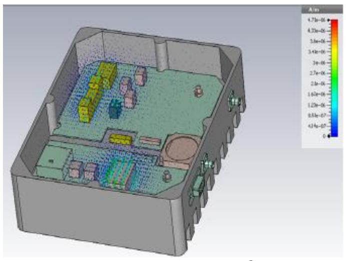


Fig. 7. The obtained result of the analysis of the magnetic field strength.

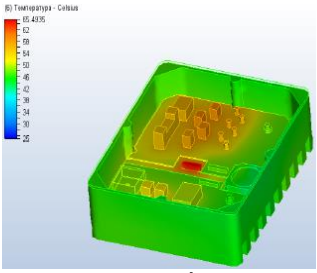


Fig. 8. The result of modeling the thermal regime of the block.

3 Methodology for assessing the electromagnetic characteristics of PB

High density element placement is widely used in modern PB designs. However, this leads to a large number of electromagnetic interference problems between the PB and the product body. This is especially true for large REM with several PB [6]. Therefore, the EMC issue of the PB should include a section on the interaction between the PB and the housings.

In this paper, the equivalent dipole model is extended to represent PP in closed rooms. This technique is attractive because of its computational simplicity and independent schema information. However, the equivalent dipole models found either from the solution of the inverse problem or from the genetic optimization of the algorithm do not work in closed constructions. Such an example is shown in Fig. 9, where both a full field simulation and an equivalent dipole simulation outside the predicted field, excited in the inside of the case at frequencies of 300-600 MHz, were carried out.

The complete field simulation, which served as a reference for the measurement accuracy of the equivalent model of both the PB and the body, was modeled by the method of moments. Whereas in the equivalent dipole model, the PB has been replaced by an equivalent model consisting of dipoles and groundings obtained from the near-field scan in free space. It was found that both results are completely inconsistent [7]. One of the possible reasons is that in free space the equivalent model represents only the electromagnetic excitation of the PB, but not the interactions between the PB and the body. Accurate indoor models require an equivalent representation for both emitting sources and the PB-housing interactions.

PB 80×50×15 mm in a housing 100×70×40 mm, with a hole in the center of the cover 20×20 mm.

Finally, complete content and organizational editing before formatting. Please take note of the following items when proofreading spelling and grammar:

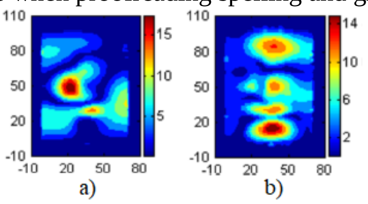


Fig. 9. The region of the microwave amplifier inside the case, obtained by modeling the PB: a) with a full field model and b) free space equivalent model.

When studying this project, it was found that due to the physical presence of the PB, changes occur during wave propagation, which affect the radiation to a greater extent than the changes in the PB currents in closed rooms. This effect is the most important factor characterizing the interaction between the PB and the body.

Other effects are caused by multiple interactions such as changes in current distribution, radiation loss and impedance. Thus, the equivalent model should represent not only radiation, but also the gross physical presence of the PB, for example, its plane of the earth and the dielectric body. For this purpose, the equivalent model is extended to explicitly include the ground plane and dielectric. This model is called “dipole - dielectric - conducting plane”, which is a general representation of the PB, a model in free space.

After the PB is installed inside the case, there will be many interactions, including some factors, such as multiple reflections of induced currents and damping of PB fields, etc.

The electromagnetic characteristics of the PB are also affected. But equivalent models obtained from near-field scanning in free space do not reveal these effects. Therefore, in order to establish equivalent models in closed spaces, multiple interaction effects on SP must be additionally modeled [8].

As a source of PB radiation, as a rule, the current distribution of currents, impedance and physical presence of the PB itself are taken. According to this model, a number of experiments and simulations were carried out to check the electromagnetic characteristics of the PB both in free space and in a closed space.

The test was carried out from a case made of copper with a thickness of 1 mm with geometric dimensions of 100×70×40 mm. The housing cover has a 20×20 mm hole as shown in Fig. 10. When the PB was placed in the housing, the lid was sealed with copper tape. The cutoff frequency for this design is calculated by the formula:

$$F_{cmm} = \frac{1}{2} \cdot \sqrt{\frac{\frac{m^2}{a} + \frac{n^2}{b} + \frac{p^2}{c}}{\varepsilon\mu}}, \qquad (4)$$

where ε and μ are the dielectric constant and permeability of the media; a, b and c - the geometric dimensions of the box ($a \geq b \geq c$); m, n, and p are ordinal numbers ($m = 1$, $n = 1$, $p = 0$). The cutoff frequency for this box is about 300 MHz.

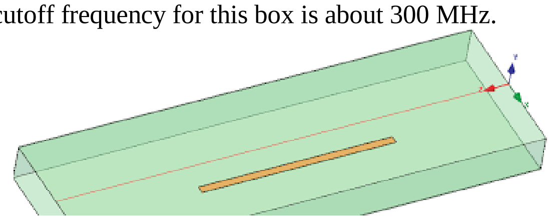


Fig. 10. Test development appearance.

One of the main characteristics, which is a radiating source of the PB configuration in the case, is the current distribution on the PB [9]. The microwave amplifier was chosen as the emitting source, and it was compared with the distribution of currents in free space and in a closed structure. One end of the track was connected to a 1 V voltage supply with a 50 Ohm resistance, and at the other end of the track, a 50 Ohm load was terminated. The currents were obtained by numerical simulation of the PB based on the methods of moments, as shown in Fig. 11. In a confined space, the PB model was located 8,5 mm above the bottom of the hull. Identical meshes were used for PB, both in free space and in a closed environment.

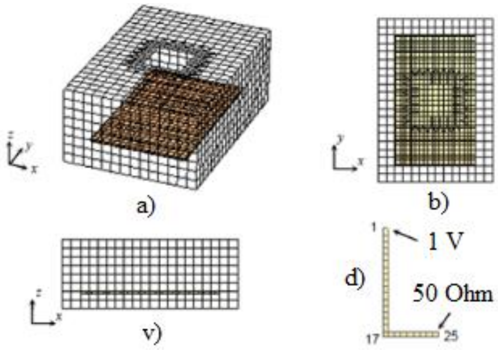


Fig. 11. Complete model of microwave amplifier inside the case: a) 3D model; b) Top view; v) Side view; d) Track segment number.

In Fig. 12 shows the current distribution at a frequency of 500 MHz, showing the entire intensity map on the upper surface of the structure and a detailed view along the microwave amplifier. This frequency is below the cutoff, so there are only localized modes. It is noticed that the current distribution in a closed environment is almost identical to that in free space.

The current distribution at the higher frequency of 600 MHz is shown in Fig. 13. However, the change in the current distribution in a closed environment is not significant (<1% at 600 MHz). For an approximate equivalent model, it is safe to assume that the change is negligible. This means that the equivalent dipoles obtained from the near-field scanning in free space are still able to reflect the current distribution of the RI in enclosed spaces.

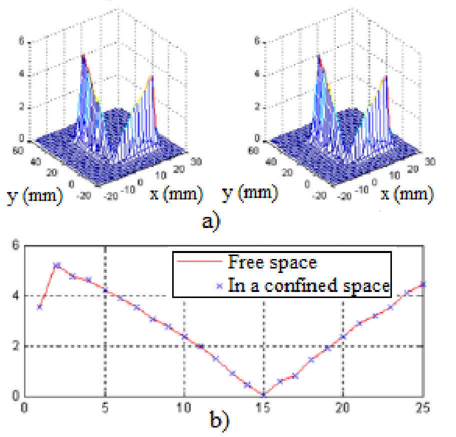


Fig. 12. Current distribution on the microwave amplifier board in free space and in the test box at frequency 500 MHz: a) Map of frequency distribution above PB;b) Observation along the track.

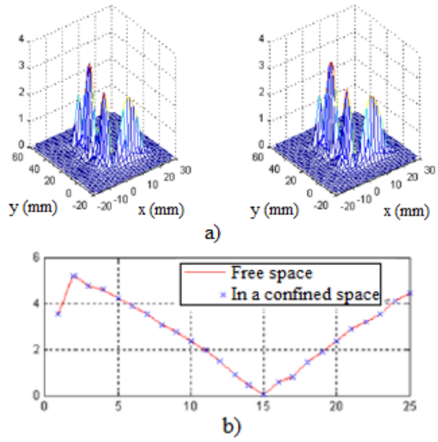


Fig. 13. Current distribution on the microwave amplifier board in free space and in the 600 MHz test box (continued): a) Frequency distribution map above the PB; b) Observation along the track

Radiant loss is the ratio of the power emitted from the transmitter to the power supplied to the transmitter [10]. This is an indicator of the efficiency of the PB as an emitting source. Equivalent dipoles represent only the radiated fraction of the total power. Therefore, if the radiation loss is significantly altered by multiple interactions, then it should be taken into account in equivalent models. Experimental measurements with a vector analyzer are a convenient way to characterize radiation losses. For a PB microwave amplifier, the source end of the track is designated as port 1, and the end load as port 2 (both ends are connected to the vector analyzer through 50 Ohms, through a coaxial frequency connector (SMA)). The dissipation parameters S_{11} (reflected power) and S_{21} (transmitted power) have been measured, then the power loss can be calculated using the following formula:

Total radiation loss =

= losses + other losses =

$$= -|S_{11}|^2 - |S_{21}|^2. \quad (5)$$

Although the measurement includes other losses, such as induced current losses, radiative losses account for the bulk of the total losses. The measurements were carried out in free space and in the case independently of each other. The results are shown in Fig. 14. Up to 600 MHz, free-space and closed-loop losses are not significant. Almost the same fraction of power is applied to a board that is fully incorporated into an equivalent dipole model derived from a near-field scan in free space.

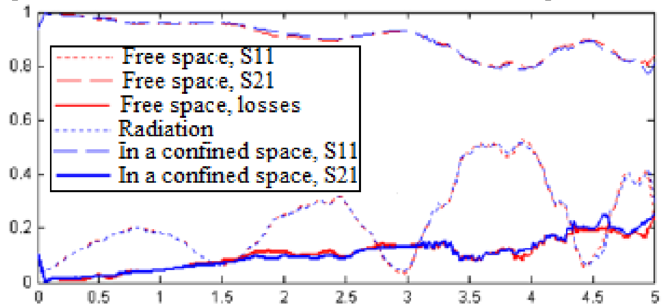


Fig. 14. Parameters of radiation losses of the microwave amplifier board in free space.

4 REM protection against mechanical external influences

External mechanical influences cause from 30 to 50 percent of failures in the operation of the REM, and also lead to a decrease in the accuracy, stability and reliability of the operated device.

Therefore, it remains important to ensure the stability of the functioning of the REM under mechanical influences and the development of ways to protect the REM from destabilizing facts [11].

Mechanical influences arise from external loads, such as shocks, acoustic noises, earthquakes, vibrations of engine parts, overload, in some cases, the cause may also be personnel negligence. Moreover, mechanical influences can be associated with the object - the carrier of the RES and occur during its operation on a moving object, and act during transportation, as well as during an earthquake or explosion. In land transport, mechanical influences are caused by maneuvering or braking at high speed, which leads to such types of them as shock, jolts, shaking. If we talk about vibration, then it can occur when the wheels beat against the rail joints or the road seams. It is also worth noting the effect of wind on the antenna devices of the radio-electronic complex.

Various parameters are used to describe certain mechanical effects. Harmonic vibrations are characterized by frequency, amplitude, acceleration. Impact loads - the number of single impacts or their series, the duration of the impact pulse and its shape, the instantaneous velocity upon impact, the movement of the colliding bodies. Linear acceleration is determined by acceleration, duration, sign of acceleration.

As a result of mechanical influences (vibrations, shocks, etc.), the following types of damage occur [12]:

- violation of sealing due to the appearance of cracks in metal-to-glass junctions, welded and adhesive seams;
- failure of detachable and one-piece electrical contacts;
- complete destruction of the body or its individual parts from mechanical resonance and fatigue;
- displacement of the position of the controls and settings;
- breakage of assembly connections;
- peeling of printed conductors;
- layering of multilayer printed circuit boards;
- destruction of ceramic substrates of integrated circuits;
- failure of mechanical assemblies (bearings, gearing, fasteners, etc.).

In addition, mechanical influences lead to interference in information transmission channels and a decrease in the accuracy of the REM operation.

It should be noted that equipment failures due to mechanical influences are recoverable after their removal or weakening and non-recoverable [13]. An example of the former is a change in the parameters of components and the occurrence of electrical noise. An example of the latter is the breakage and short-circuits of electrical connections, peeling of conductors of printed circuit boards, violation of fastening elements and destruction of supporting structures.

The most common ways to protect REM from mechanical stress are shown in Fig. 15 [14]:

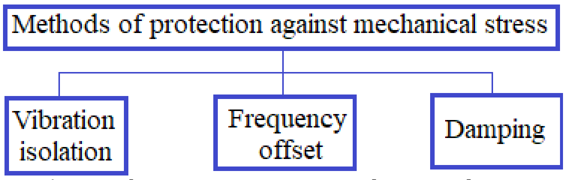


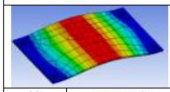
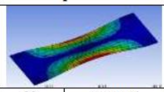
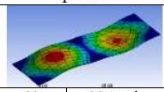
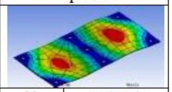
Fig. 15. The main ways to protect electronic devices from mechanical external influences.

The greatest application is currently received by frequency offset, which consists in changing the ratio between frequency disturbances and the natural frequency of the structure. This method is aimed at reducing or eliminating resonant oscillations.

Such types of frequency tuning implementation as changing the mounting method, the area and thickness of the printed circuit board, as well as the use of stiffeners [10] have become widespread.

An increase in the mounting points of the boards from four to seven increases the natural vibration frequency by more than 3 times (Table 1).

Table 1. Natural frequencies of boards at different fixing options.

Point mount types							
Four attachment points		Five attachment points		Six attachment points		Seven attachment points	
							
№	Natural frequency value	№	Natural frequency value	№	Natural frequency value	№	Natural frequency value
1	576,08	1	1397,7	1	1916,5	1	2124,9
2	1043,7	2	1610,1	2	1962,8	2	2242,2
3	1573,5	3	1842,3	3	3005,2	3	3005,1

The influence of the increase in the attachment points on the second and third natural frequencies is not so significant.

The main disadvantage of frequency offset is to reduce the useful area of printed circuit boards for the installation of electrical radioelements.

Another method of protection against mechanical stress is vibration damping due to the inclusion of special layers of vibration-absorbing materials in the PB design. The damping of vibrations in this case occurs due to an increase in the dissipation of vibration energy due to the forces of internal friction.

The use of damping coatings makes it possible to reduce the amplitude of resonant vibrations, while the shift of natural frequencies of printed circuit boards with coatings can change both up and down. The direction of displacement depends on the choice of damping material and is largely determined by the value of Young's modulus. Damping coatings are divided into soft and hard. Rigid coatings with a modulus of elasticity of 100 - 1000 MPa are effective for reducing vibration at low and medium frequencies. Examples of such materials are plastics. Soft are coatings, the modulus of elasticity of which is of the order of 10 MPa. They are used to reduce high frequency vibrations. Among them are soft rubbers and plastics, various mastics.

To analyze the effect of coating thickness on natural frequencies, a model of a printed circuit board of a microwave amplifier operating at frequencies of 300-600 MHz (Fig. 16, Fig. 17) with damping layers made of materials with different values of Young's modulus: 5·105 Pa and 155,7·105 Pa, which corresponds to soft and hard surfaces.

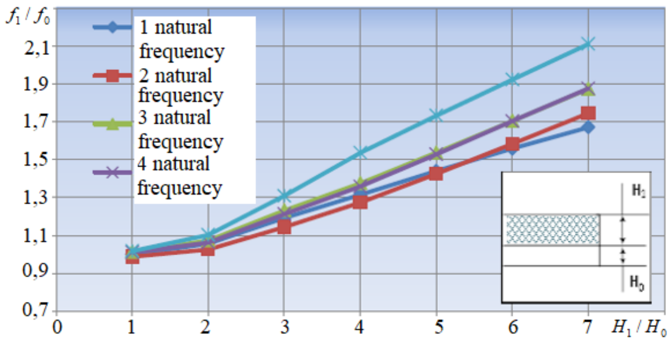


Fig. 16. Natural frequency versus thickness for a hard coating.

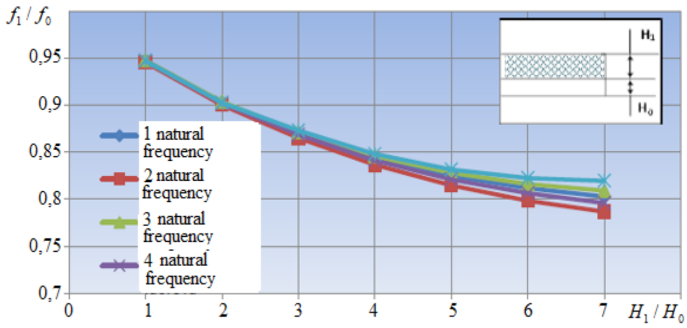


Fig. 17. Natural frequency versus thickness for a soft coating.

Rigid PB coatings shift natural frequencies to the right, and an increase in coating thickness leads to an increase in natural frequencies. The use of soft coatings, on the other hand, shifts the natural frequencies to the left relative to the natural frequencies of the uncoated PB. And, an increase in the thickness of the coating causes a decrease in the values of natural frequencies.

In studying the influence of the values of the Young's modulus of the coating on the natural frequencies, it was found that a change in the Young's modulus from 5 MPa to 6 GPa leads to an increase in the natural frequencies by 4-5 times.

Numerous theoretical and experimental studies of structures of both types have shown that the use of a damping layer of only a few tenths of a millimeter in structures with an inner layer makes it possible to reduce the amplitudes of resonant oscillations several times.

In structures with an outer layer, this effect can be achieved when the thickness of the vibration-absorbing coating is 5-10 times the thickness of the carrier layer.

One of the advantages of using vibration-polishing coatings is to reduce the amplitude of resonant vibrations and change the natural frequencies in a given direction, insignificant with relative stability of the mass and dimensions of the structure. However, the maximum efficiency of vibration-absorbing materials is most often achieved at room temperature and they are intended for operation in the temperature range from minus 10˚C to + 50˚C.

The third method of protection against mechanical stress is vibration isolators. In most REM designs, they are used to protect against impacts and differ in the type of elastic element and design. This is a consequence of a wide range of operating conditions [11, 12]. In this case, the task of the designer is to choose a vibration isolator that best meets the technical specifications.

External influences have a significant impact on the operation of the REM [13]. Therefore, an important task of the designer is to carefully consider the parameters of external influences and the choice of an adequate method for protecting the electronic equipment.

Conclusions

In the course of the work, a method was proposed for the optimal layout of REM units, taking into account the electromagnetic and thermal characteristics, adapted to the existing production conditions.

The technique includes procedures for the initial layout and optimization of the block design, the creation of a 3D model and its adaptation for further analysis.

Practical application of the technique to optimize the layout of the microwave amplifier of a radio station allowed us to obtain the following results:

- the temperature of the most heat-loaded element was reduced by 6% due to an increase in the depth of the bore in the body by 1 mm;
- the maximum temperature inside the block was reduced by 16% after the installation of a local forced air cooling system;
- the intensity of the electric and magnetic fields in the frequency range of 300-600 MHz was reduced by 3% after optimization of the board routing, as a result of which the lengths of the printed conductors were reduced;
- the noise immunity of the structure at a frequency in the frequency range of 300-600 MHz was increased by 10% due to the installation of the screen.

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