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Procedure of Complex Analysis of Mechanical Properties of Printed Circuit Boards in Electronic Modules

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Abstract : This article describes a procedure of printed board so fradio electronic systems (RES) with consideration for impact of mechanical load son the basis ofcombined application of CAE analysis and laboratory tests of experimental printed boards. The model so foscillations of standard RES printed circuit designs in the form of plate, used upon analytical solution ofthe problem in the simplest cases, are considered. The final task is to optimize positions of printed circuit fixation.In addition, the main stages of simulation of radio electronic means in Creo Parametric system using specialized module Creo Parametric Mechanica are considered. Application of the proposed procedures upon designing of module on printed circuit is demonstrated.

Elements of mechanical theory, mathematical simulation and finite element analysis have been applied (CAE).

The proposed procedure facilitates significant speed-up of development of radio electronic means due to systematic application of CAE analysis and systems of automatic designing. Another feature is application of results of laboratory tests of experimental printed boards, thatis, development of ever-growing database containing information about ultimate mechanical loads of various printed boards manufactured by different technologies.

Keywords : Radio electronic means, radio electronic modules, models of board oscillations, optimization of printed board design, loading, mechanical analysis, CAE analysis, testing of printed boards.

1. INTRODUCTION

Automation means are widely applied with the aim of decrease in material and time expenditures involved in production of radio electronic means (BarabanovV.F.,et al., 2011). In addition to the aspects of designing the problems of engineering, operation, maintenance and disposal of products are solved by means of software complex.

The main unit of RES is radio electronic module, which is load bearing structure with mounted electronic components (including micro electronic units (Achkasov A. V., et al., 2014)) and which is mounted in higher level modules (units, control panels, racks, cabinets). Board its elfisa complex item, containing embedded distributed capacitors and resistors (Muratov A. V.,et al., 2006) and (Muratov A. V., et al., 2006).

Upon production of radio electronic device, of specialized target in particular, the specimen at final designing stages is intensively tested for climatic and mechanical impacts occurring upon operation.

The revealed draw backs of designs hould bee liminated and this process is sufficiently complicated, sometimes it requires for serious modifications of the product. It would be more reasonable at designing stage, using computer simulation (CAE analysis),to test printed boards for resistance against various loadings, including mechanical. In this case the amount of modifications can be significantly decreased, saving time and costs of designing.

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Radio engineering industry applies various high-level CAD systems, covering wide range of RES development stages. One of such systems is Creo Parametric (former Pro/Engineer Wild fire) (Mineev, M. A., 2008). Unfortunately, the mentioned system cannot simulate mechanical properties of such complex units as multilayer printed boards (Muratov A. V.,et al., 2006), where as they are the main components of overall device. Multi layer printed board sits elfisa complex design, comprised of numerous elements: interlayer dielectrics, switching conductors, film resistors and capacitors, unpackaged microcircuits and others.

Simulation its elfisalso sufficiently complicated due to the influence of numerous factors: materials, production process, design and others. At the same time, upon analysis of mechanical properties of multilayer boards the values of allowable loading should serve as guides. These values can be obtained only in laboratory tests of experimental printed boards including statistical processing of the results.

2. EXPERIMENTAL

Algorithm of complex analysis of mechanical properties of printed boards in radio electronic modules

This work proposes an algorithm of optimum designing of radio electronic modulesby means of study into mechanical properties of multilayer printed boards (Fig. 1). This algorithm applies test results of experimental specimens as estimation criteria of mechanical reliability. It takes in to account ultimate values of vibrations, shocks, static loadings of printed boards with various number of layers, made of various materials and by various processes.

Similar approach was applied in (Lozovoi, I. A.,et al., 2011) and (Lozovoi, I. A.,et al., 2013)with regard to radio electronic modules of the first fragmentation level.

Laboratory tests of experimental multilayer printed boards can be performed according to the schedule of IPC-TM- 650 (IPC-TM-650 Test Methods Manual, 2003). The mentioned procedure includes a set of mechanical and electric tests, as well as inspection of dimensions. In order to speed up material ageing in the board sitis recommended to apply thermal cycling described else where (= O752, .,et al., 2008).

The mentioned procedure includes heating of products to pre determined temperatures, holding and cooling, this procedure is repeated several times. The number of thermal cycles depends on operationc onditions: the more severe are the conditions, the higher is their number.

Formulation of the optimum designing is given in block No.1. According to specifications, mechanical impacts influencing on the developed item during operation are summarized.

In order to initiate analysis of reliability of radio electronic device all required information is acquired (block No. 3).

It is necessary to obtain data on elemental base, materials and their properties (F. L. Matthews and Rees D. Rawlings, 1999), as well as on technology of manufacturing of multilayer board. The bottle necks of design in terms of mechanical reliability are detected (IPC, 2010. IPC-6012C-2010),(GOST 30630.1.2-99, 1999).

The data is obtained from ever-growing database (block No. 2), which contain data on vibrational, shock and thermal properties of active and passive elemental database. It also contains information about physico chemical properties of engineering materials of radio electronic means and printed boards.

The engineering process can follow two scenarios. If the design is simple, than the simulation can be speeded up by means of analytical method. In more complicated cases, which are dominant, CAE analysis is applied. The scenario is defined in blockNo. 4.

Analytical solution of the problem (block No. 5) includes the use of mathematical models for typical methods of board mounting. They areas follows: clamping, free bearing or unfixed edge of plate or beam.

The analytical solution determineseigen oscillation frequencies of board design, stresses in certain design sections under the impact of static loadings and shocks.

Block No.6 checks sufficiencyo f the results of analytical solution. If the results satisfy designer, then further designing stages are approved. If the analytical solution does not provide sufficiently accurate and definite results, or analytical methods cannot be applied to the, then engineering analysis is applied on the basis of finite element method (blockNo. 8).

This method should be based on 3D model of the developed design.

According to specifications some limitations are implied to the design, such as fixations, loadings and materials; then the simulation is performed (blockNo. 11). Creo Parametric system is selected as a basis, including modules of CAE analysis.

It provides possibility of the most popular variants of simulation of mechanical loadings (static, modal, and dynamic analyses).

According to specifications, the required testing modes are selected (blockNo. 28).

Creo Parametric system has powerful post-processing program, which arranges analysis results in the form of diagrams (block No. 12). It is possible to determine stresses in various locations of the design with highlighting of problematic areas.

Block No. 8 includes also procedures of laboratory testing of experimental printed boards according to international standard IPC-TM-650 (IPC-TM-650 Test Methods Manual, 2003). Mechanical properties of various boards manufactured by various procedures are analyzed (block No. 9). Then the data, obtained in block No. 10, are statistically processed and transferred to specialized database (block No. 13). It includes data on ultimate values of vibrations, shocks and static stresses of printed boards of various designs, various precision types and various manufacturing procedures. It should be mentioned that laboratory tests of one board type can be performed only once and then to use the obtained data in numerous projects implemented in different companies.

After CAE analysis in block No. 14 the results are verified using database (block No. 13). If the obtained values of mechanic stresses exceed the threshold of reliable operation, or eigen frequencies in the operation range, then the solution is adopted on optimization of board design (block No.23). The design can be either modified (block No. 24), or materials with another properties are used (block No. 25), or topology is changed (block No. 26), or another manufacturing technology is applied for the board (block No. 27). Subsequently the overall cycle of CAEanalysis is repeated (blocks Nos. 11, 12).

If the simulation results are satisfactory (block No. 15), then the solution of manufacturing of experimental design is adopted (block No. 16) in accordance with international and Russian standards (IPC/EIAJ-STD-001D, 2010), (GOST R MEK 61192-2-2010, 2010), including its testing on vibrating tables (block No. 18). Herewith, the stipulated modes are applied (GOST 23752.1-92, 1992) (block No. 17). BlockNo. 19 verifies conformity of mechanical properties of manufactured item with the preset requirements. If the design did not pass tests, then it should be optimized (block 23) including development of modified experimental specimen.

If the design passes laboratory tests, then it is tested in actual operation conditions (block No. 20), where it affected by other factors influencing on reliability (moisture, dirt, salt spray and others).

Block No. 21 verifies conformity of properties of the designed item with the specification, and in the case of positive solution the item is delivered to customer (block No. 22). Otherwise, it is required to repeat the process of design modernization.

Upon analytical solution of the problem (block 5) the analysis of mechanical impacts and determination of dynamic properties, loadings, resonant frequencies of RES designs are based on the use of partial differential equations of elasticity theory and oscillation theory (Gel' P. P.,et al., 1984)and (Talitskii E. N., et al., 2001). Let us consider basic models of main analytical problems of mechanical properties of RES designs. For some standard RES designs (printed boards) the model of plate transversal vibrations is applied.

Mechanical vibrations in homogeneous plate are described as follows :

$$c^2\left(\frac{\partial^2\xi}{\partial x^2}+\frac{\partial^2\xi}{\partial y}\right)+f(x,y,t) = \frac{\partial^2\xi}{\partial t^2} \quad (1)$$

where

$$c^2 = T/\rho ; \quad (2)$$

$$f(x, y, t) = \frac{F(x,y,t)}{\rho}; \quad (3)$$

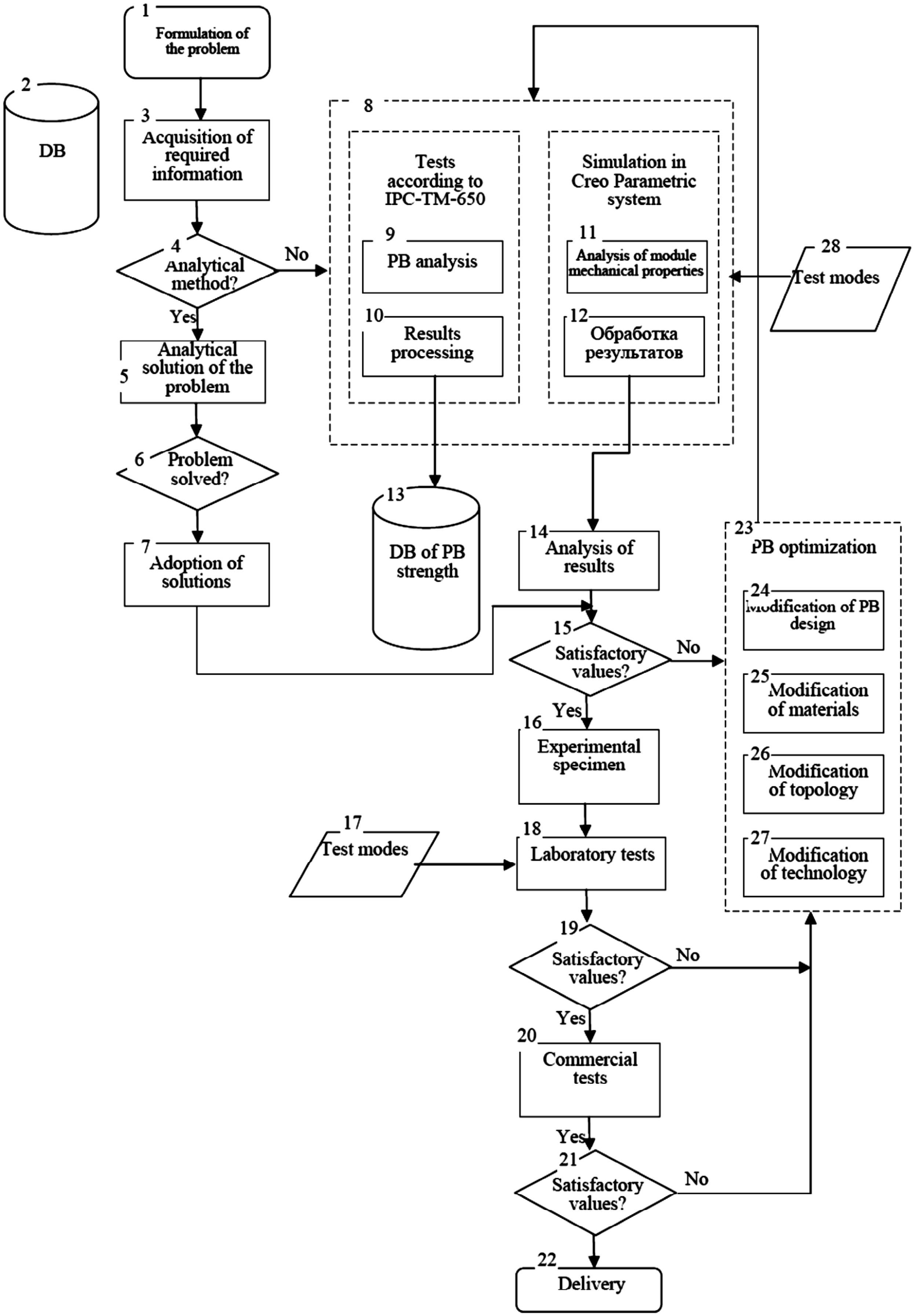

Fig. 1. Algorithm of complex analysis of mechanical properties of printed circuit boards in electronic modules.

T is the plate stress; F(x, y, t) is the applied force.

When the design is considered as elastic plate, the partial differential equation of the 4th order is used:

$$D\left(\frac{\partial^4\xi}{\partial x^4}+\frac{\partial^4\xi}{\partial x^4\partial y^2}+\frac{\partial^4\xi}{\partial y^4}\right)-\frac{\gamma\delta}{g}\omega_0{}^2\xi = 0 \quad (4)$$

where $D=\frac{E\delta^2}{12}\left(1-\sigma^2\right)$ is the plate cylindrical rigidity; σ is the Poisson ratio; γ is the plate specific weight; ω_0 is the plate eigen frequency; δ is the plate thickness.

Boundary conditions are as follows :

– plate edges are freely mounted $$\xi = 0; \frac{\partial^2\xi}{\partial x^2}+\sigma\frac{\partial^2\xi}{\partial y^2}=0 \quad (5)$$

– plate edges are rigidly fixed $$\xi = 0; \frac{\partial\xi}{\partial x}=0; \quad (6)$$

– plate edges are free $$\frac{\partial^2\xi}{\partial x^2}+\sigma\frac{\partial^2\xi}{\partial y^2} = 0 \quad (7)$$

$$\frac{\partial^2\xi}{\partial x^2}-(2-\sigma)\frac{\partial^2\xi}{\partial x\partial y} = 0 \quad (8)$$

When the plate is exposed to the action of loading (external force) varying according to harmonic law:

$$F(x, y, t) = f(x, y)\sin\omega t \quad (9)$$

The equation of forced oscillations is written as follows:

$$D\Delta^2\xi-\frac{\gamma\delta}{g}\omega^2\xi-f(x,y) = 0 \quad (10)$$

where $$\Delta^2\xi = \frac{\partial^2\xi}{\partial x^2}+2\frac{\partial^2\xi}{\partial x\partial y^2}+\frac{\partial^2\xi}{\partial y^2} \quad (11)$$

The Lagrange equation sing eneralized coordinates, which make it possible to determine vibration properties, that is, motion, speed, acceleration, by per turbing force are also used as mathematical base for simulation of vibration actions in RES designs.

$$\frac{d}{dt}\left(\frac{\partial E_k}{\partial\dot{q}_k}\right)-\frac{\partial E_k}{\partial q_k}-F_k = 0; \quad (12)$$

where q_k are the generalized coordinates $(k\equiv\overline{1,n})$;

$$\dot{q}_k = \frac{\partial q_k}{\partial t};$$

E_k is the kinetic energy; F_k– is the generalized 9 external) force.

In the case of potential character of generalized forces :

$$F_k = -\frac{E_n}{\partial q_k} \quad (13)$$

where E_n is the potential energy, the equation is rewritten as follows:

$$\frac{d}{dt}\left(\frac{\partial E_k}{\partial\dot{q}_k}\right)-\frac{\partial E_k}{\partial q_k} = 0. \quad (14)$$

and as follows : $$\frac{d}{dt}\frac{\partial L}{\partial\dot{q}_k}-\frac{\partial L}{\partial q_k} = 0, \quad (15)$$

where $L = E_k - E_n$ is the Lagrange function.

Simulation of one-dimensional oscillations indesigns is based on the Lagrange equation for system with one degree of freedom, where expressions for kinetic and potential energies are as follows:

$$E_k = m\dot{\xi}^2/2,\ E_n = m\xi^2/2 \tag{16}$$

where m is the weight; $\xi = \frac{\alpha\xi}{dt}$;

$\xi = q - q_0 -$ is the offset (deviation) of coordinates q from equilibrium value q_0; k is the coefficient of design rigidity.

When oscillations in such system are small, the Lagrange equations are rewritten as follows:

$$L = m\dot{\xi}^2/2 - k\xi^2/2 \tag{17}$$

and the differential equation is rewritten as:

$$m\ddot{\xi} + k\xi = 0 \tag{18}$$

or

$$\ddot{\xi} + \omega_0^2\xi = 0, \tag{19}$$

where

$$\ddot{\xi} = \frac{\alpha^2\xi}{dt^2};$$

$$\omega_0 = \sqrt{k/m},$$

In the case of oscillations under the action of external force (forced oscillations) Eq. (19) is as follows:

$$\ddot{\xi} + \omega_0^2\xi = \frac{1}{m}F(t) \tag{20}$$

When the attrition forces F_m act in the considered subject, the Lagrange equation is as follows:

$$m\ddot{\xi} + k\xi = -\alpha\dot{\xi} \tag{21}$$

or

$$\ddot{\xi} + 2\lambda\dot{\xi} + \omega_0^2\xi = 0, \tag{22}$$

where $F_m = -\alpha\dot{\xi}$; a is the attrition coefficient; $a/m = 2\lambda$ is the decay factor.

Equation of forced oscillations of such system is as follows:

$$\ddot{\xi} + 2\lambda\dot{\xi} + \omega_0^2\xi = F(t). \tag{23}$$

For practically important case, when the impact is harmonic, wehave:

$$\ddot{\xi} + 2\lambda\dot{\xi} + \omega_0^2\xi = \frac{F_0}{m}\sin(\gamma t)\ m \tag{24}$$

where

$$F(t) = F_0\sin(\gamma t)/m \tag{25}$$

For plane and spatial subjects the model of mechanical systems is applied with several degrees of freedom q_i, where I = 2; 3. In this case the system energy is calculated using quadratic forms:

$$E_k = \frac{1}{2}\sum_{i,k=1}^{n} m_{i,k}\dot{q}_i\dot{q}_k \tag{26}$$

$$E_n = \frac{1}{2}\sum_{i,k=1}^{n} k_{i,k}q_iq_k$$

where $q_i, \dot{q}_i$ are the generalized coordinates and their derivatives with time;

$$m_{ik} = m_{ki}, \quad k_{ik} = k_{ki}, \quad (i,k = \overline{1,n}).$$

Then, we have the following Lagrange equation :

$$\sum_{k=1}^{n}(m_{ik}\ddot{q}_k + k_{ik}q_k) = 0. \tag{27}$$

Equation (23) can be also applied for analysis of impact loadings; here with, equivalent frequency f_0 and parameters of equivalent shock pulse (acceleration a_0 and duration t_0) are used for external shock impact (Pestryakov V. B., et al., 1992)

$$a_0 t_0 = \int_0^t a(t)dt \tag{28}$$

where $a(t)$ and t are the amplitude and duration of actual pulse, respectively.

Formulation of the problem of board design optimization

The problems of design optimization are also solved upon designing of radio electronic modules. One of such problems of optimization of mechanical properties of radio electronic modulesis reduced to basic Eq. (29), the process is reduced to determination of minimum amplitude of eigen oscillations of radio electronic modules. However, it is required to take into account that such engineering tasks, as location of components, weight, dimensions, have higher priority.

The values of target function are determined by differential equation of forced oscillations (10, 11), which describe mechanical oscillations of plate upon external actions:

$$\text{extr}\,\xi\,(X, \delta), \tag{29}$$

where $\xi\,(X, \delta)$ is the target force of eigen oscillation amplitude of radio modules:

$$\xi\,(X, \delta) \to \min, \tag{30}$$

where X are the coordinates of mounting point, δ is the thickness of printed board.

Parametric limitations on the research area:

$$x_i \neq x э_j + \Delta;$$

$$y_i \neq y э_j + \Delta; \tag{31}$$

$$0 \leq y \leq b \tag{32}$$

where x_i, y_i are the coordinates of mounting point; x_{RCj}, y_{RCj} are the coordinates of printed board component(radio component, printed track and so on); $\Delta$is the tolerance; ais the PB length; bis the PB width.

Therefore, taking into account Eqs. (31) and (32) the limitations of the research area:

$$D_x = \{X | x_i \neq x э_j + \Delta;\; y_i \neq y э_j + \Delta;$$

$$0 \leq x \leq a\,;\, 0 \leq y \leq b\}, \tag{33}$$

$$D_\delta = \{\delta |\, \delta_1 \leq \delta(w) \leq \delta_2\}, \tag{34}$$

The limits, δ_1 – PB minimum thickness, δ_2 – PB maximum thickness, are determined upon designing of printed board and depend on many parameters, namely: number of PB layers, electrical and electromagnetic properties of materials, cost, engineering limitations and so on.

$$\delta(w) = k \cdot w + \delta_1 \tag{35}$$

where $\delta(w)$ is the linear function determining the PB thickness; wis the integer equaling to 0, 1, 2, 3…n, determining the number of iterations; k is the discretization coefficient, $k < 1$, the lower is k, the lower is the discretization step.

The following limitation should be satisfied upon optimization and designing of radio modules:

$$f_p \leq 2.f_{op} \tag{36}$$

where f_p is the eigen frequency of oscillations of radio electronic modules; f_{Op} is the maximum vibration frequency during product operation. However, at f_{op} higher than 500 Hz, similar frequency offset is unreasonable, in such cases polymer dampers are the most efficient, which reduces significantly the amplitude of resonant oscillations.

In addition to determination of minimum of target function (29), which is applied in the cases of radio module mounting in holes, the required mechanical properties can be provided by analysis of solutions of the differential equation (10) with enumeration of boundary conditions at PB edges, that is, rigid clamping, free mounting, or exclusion of any fixation.

2. RESULTS

As an example of implementation of this procedure a radio electronic module was simulated with regard to mechanical properties. Radio electronic module is a on-board design with four factory holes for fixation and eight holes for mounting of LC indicators of two types. Inaddition, the board also contains LEDs, electric connectors and other components.

In the initial variant the board was rigidly fixed via 4 existing holes, the surface was loaded by 10 N inj perpendicular to the board plane.

Creo Parametric software has possibility of automatic generation of grid of finite elements. The external appearance of the fixed board with grid elements is illustrated in Fig. 2.

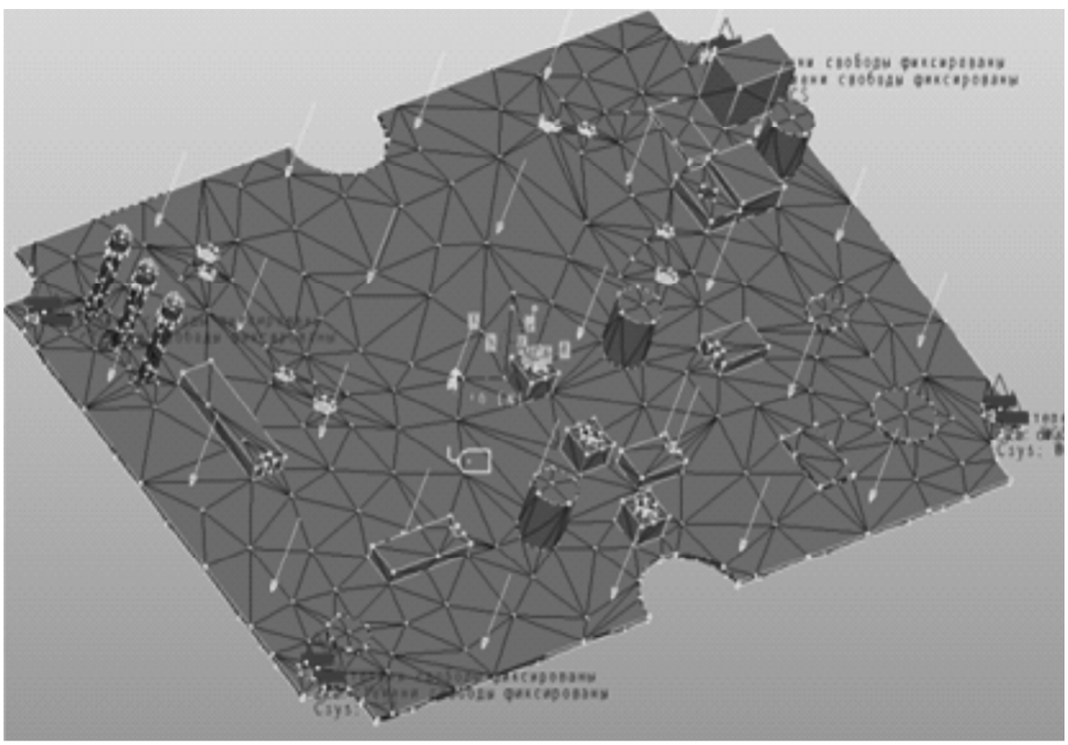

Fig. 2. Fixed board with grid components.

The number of grid elements influences on simulation accuracy. The smaller is the size of grid finite element, the higher is the accuracy, however, this leads to significant increase in analysis time, which requires for significant resources of computational platforms. Creo Parametric has the option to vary grid size invarious design elements. When increased accuracy is required, the size of elements is decreased, whereas the size of other elements can be significantly higher.

Simulation results of static mode are illustrated in Fig.3. The lighter is the contour, the higher is the board deflection.

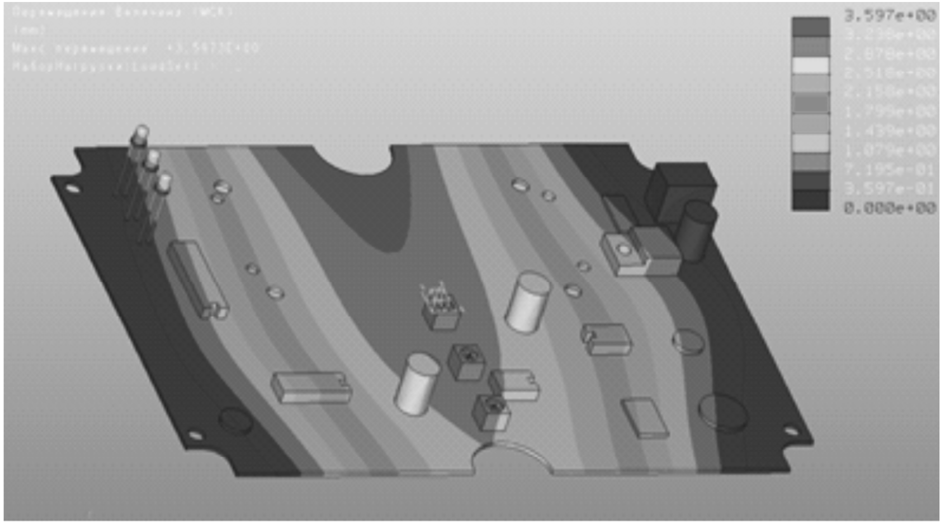

Fig. 3. Structural analysis, staticmode.

While analyzing the results in Fig. 3. it is possible to state that the maximum travelling of board sections is observed in its middle and equals to 3.5 mm, which is significant. Typical also is the existence of non-uniformly loaded sections due to board mounting configuration In addition, increased von Mises stress of board sections in the vicinity of holes was detected, equaling to 40 MPa.

Modal analysis demonstrated that the first resonance occurs at 62 Hz (Fig. 4), which is unacceptable, since the upper boundary of operational frequencies is 120 Hz. According to operational specifications it is required to provide 2-2.5 fold reserve with regard to lower boundary of resonant frequency, and the design should be optimized in order to satisfy the condition of mechanical strength upon impact of external vibration.

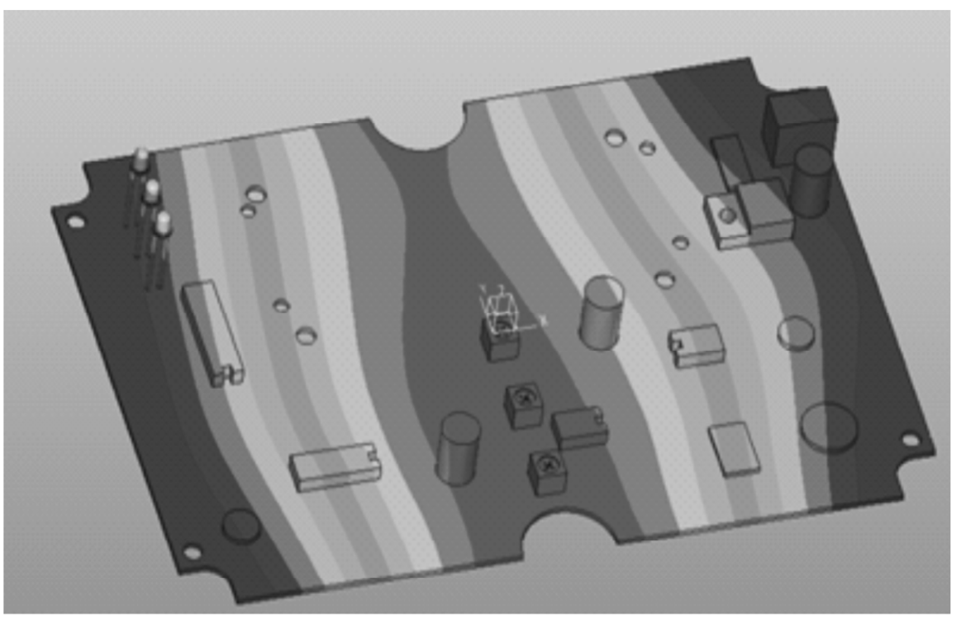

Fig. 4. Modal analysis of the PCB first resonance, 62Hz.

In order to increase eigen frequencies more rigid fixation of board is required, as well as application of materials with better strength properties or decrease in the board surface area. It is impossible to decrease the board surface area, since it has rather dense arrangement, and application of other materials lead to significant cost increase. Hence, optimization was performed by increase in board fixation rigidity.

Five variant soft he design were analyzed upon designing of radio electronic module. The final variant is illustrated in Fig. 5. The board is mounted via 8 existing holes and via 2 additional holes in the middle.

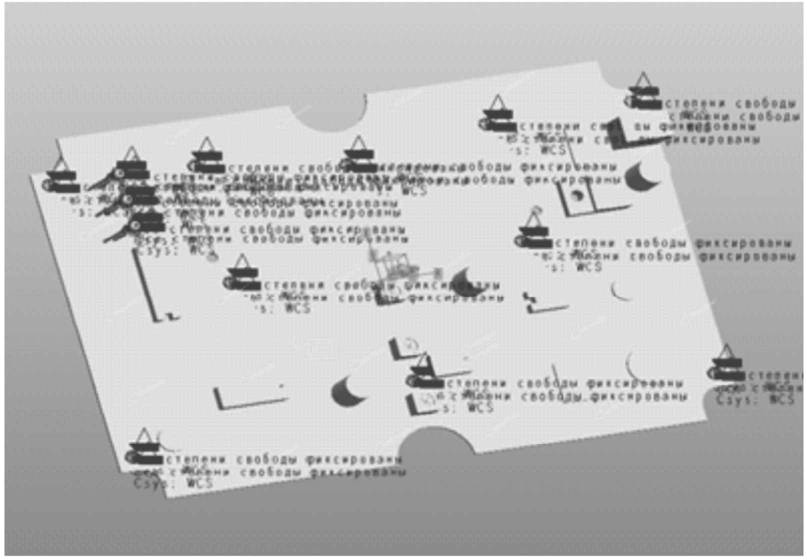

Fig. 5. The fifth variant of the design, 10 holes and 3 LEDs are fixed.

Resonance of LEDs was also revealed. It was decided to fix the LED ands in the cover. The results of static and modal analyses of optimized design are illustrated in Figs. 6-9.

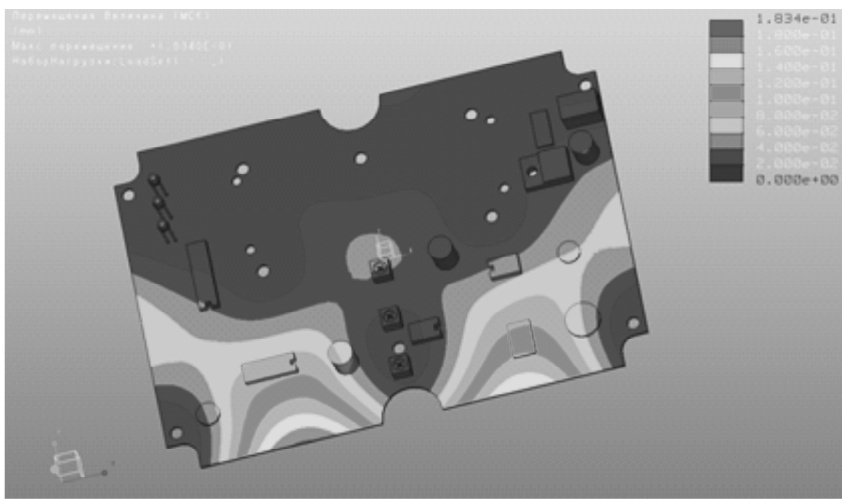

Fig. 6. Analysis of static mode off in alvariant of the design.

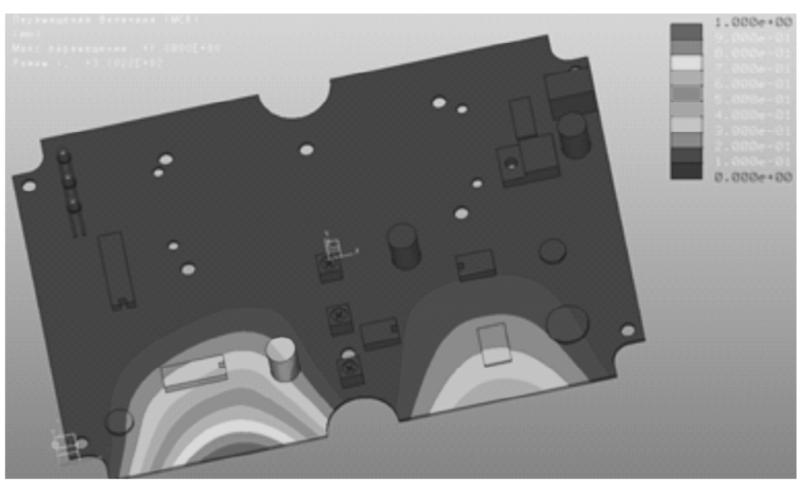

Fig. 7. The 1st resonance, 310 Hz (5th variant of the design).

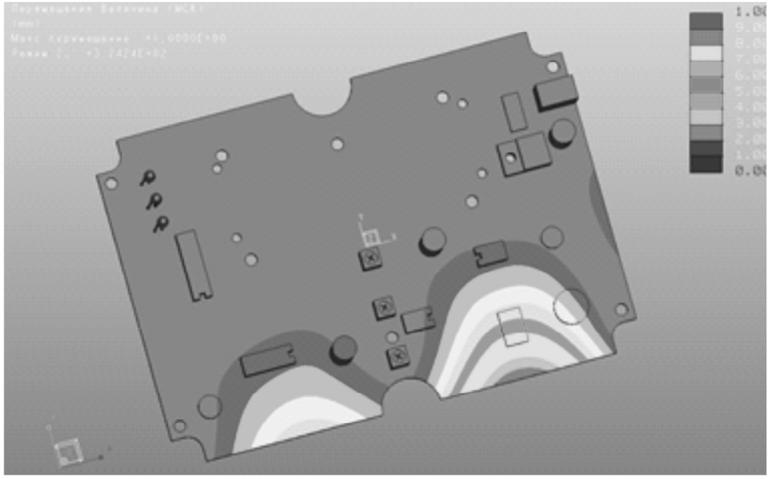

Fig. 8. The 2nd resonance, 324 Hz (5th variant of the design).

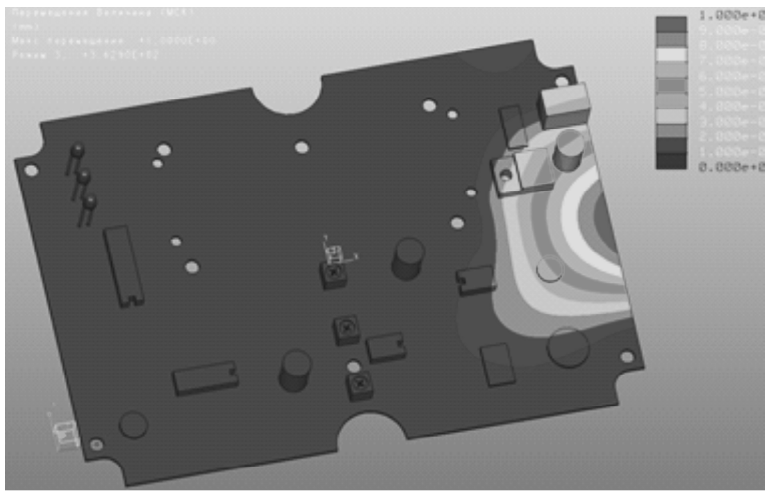

Fig. 9. The 3rd resonance, 362 Hz (5th variant of the design).

3. DISCUSSION

While analyzing Fig. 6 it is possible to state that maximum travelling of board sections equals to 0.18 mm, which is insignificant.

Results of analysis of resonant frequencies (Figs. 7-9)demonstrate that their values are higher than operational maximum of 120 Hzby 2 times and even more.

On the basis of the results it was assumed to develop an experimental specimen and to test it.

Therefore, on the basis of the given example it was demonstrated that systematic application of CA analysis significantly speeds up the designing procedure, since it is not required to develop experimental specimen for further field tests. It should be also mentioned that the highest effect is observed upon overall application of the developed designs by such engineering calculations. However, extraordinary experience is required for correct interpretation of simulation results and decision making, only qualified experts possess such experience. As a rule, the rea few such experts in the companies, they cannot pay attention to all projects due to the lack of time.

The proposed procedure improves identification of simulation results. In the future it will be possible to develop dedicated expert system (D. Waterman, 1983), (P. Jackson, 1990) on the basis of experimental data by qualified experts, thus determining the optimum designing approach. Such expert system will make it possible to speed up both designing and accumulation of required experience by recent graduates. Development of the expert system requires for extended scrupulous work and financial expenditures, however, its application will significantly reduce such expenditures.

4. CONCLUSIONS

The proposed procedure facilitates significant acceleration of development of radio electronic devices. This is supported by two factors. The first factor is based on systematic application of CAE analysis, as well as CAD systems. The second factor includes existence of dedicated ever-growing database with information about ultimate mechanical loadings of various printed boards.

Many Russian companies involved indesigning of radio electronic means usually maintain extended list of designed means where standard designs of printed boardswith unified sizes are applied. Application of the proposed procedures would allow to use this database without additional laboratory tests.

The considered models can be used upon analysis and optimization of designs of radio electronic modules (printed boards) on the basis, for instance, of algorithms proposed in (Lozovoi, I. A.,et al., 2011) and (Lozovoi, I. A.,et al., 2013). In addition, the designed items can be improved by involvement of intelligent systems of decision making (expert systems) (D. Waterman, 1983), (P. Jackson, 1990).

It is assumed that the proposed procedure will be improved further. One of the promising ways is development and application of automated systems of decision making on the basis of expert systems. This tool would improve significantly designing efficiency of radio electronic means.

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