Computer simulation possibilities of dynamic tests of large-scaled mechanical structures

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Abstract. The work is devoted to the analysis of the computer simulation capabilities of dynamic testing of large-scaled structures when exposed to acoustic noise, sinusoidal and random vibration, linear acceleration, mechanical single and multiple shocks. The simulation results obtained with regard to the regulatory requirements for the test methods for the action of external influencing factors reflect the effect of the main conceptual and technical solutions of the structures on their dynamic behaviour. Computer simulation of dynamic tests allows, on the one hand, to exclude unacceptable dynamic effects due to unsuccessful design decisions, on the other hand, can be considered as an important part of the design conformity assessment with technical requirements.

1. Introduction
The creation of competitive and efficient technical objects implies taking into account modern concepts of design and engineering, capabilities of information and computer technologies that meet international and national standards. One of these concepts is the use of a system engineering approach to the development and maintenance of objects during their life cycle. In accordance with the approaches of system engineering [1], at present, the process life cycle model is preferred, in which eleven processes are considered, one of which is the verification process. The verification procedure consists in evaluating and confirming the compliance of the object being developed with the technical requirements. There are no fundamental restrictions on the tools and technologies used for this purpose. However, it is obvious that the most adequate and reliable estimates can be obtained by mechanical testing of full-scale objects for the action of external influencing factors (EIF). This is due to the fact that only with such tests one can take into account a number of individual features of the object, forming a complex of its system properties and integral characteristics of behavior. Such features include, for example, [2] defects, design errors, primary manufacturing and assembly errors, re-placing gaps in connections, etc. As noted in [2], “some of the real parameters are random, and some are deterministic, but the parameters are manifested in the aggregate, they are interdependent, and their joint inclusion in mathematical models is difficult.”

It should be noted that during mechanical testing of full-scale objects, negative effects can be identified, caused not only by the above-mentioned individual features of a specific instance of an object, but also by fundamental design and technological errors in the design of an object and characteristic of it as a class of technical systems. Since the tests of full-scale objects are carried out at the later stages of development, the elimination of such errors is accompanied by significant time and material costs.
When it is necessary to organize and conduct mechanical tests of full-scale objects, technical difficulties are often encountered. They consist in the impossibility of carrying out tests of a full-scale object due to the fact that its overall and weight characteristics exceed the limitations of existing test equipment. In this case, the question arises about the possibility of complete or partial replacement of mechanical tests by computer simulation, which is explicitly allowed by existing standards.

Obviously, computer simulation is performed not for a specific instance, but for its ideal model, corresponding to the designer's intention. Simulation will not allow to determine the presence of individual features of an instance of an object, but it will give an opportunity of development to identify and eliminate unsuccessful decisions made during design at earlier stages.

There are no fundamental conceptual contradictions in the interpretation of the results due to the replacement of mechanical tests with computer simulations, since, in accordance with international standard [3], the result of conformity assessment should not be considered as some rigorous proof that the object complies and will always meet the established requirements. Demonstration of compliance can be carried out with varying levels of reliability and credibility, depending on the needs and capabilities. The limits of the concept of "conformity assessment" are not defined; they remain flexible [3].

One of the objectives of mechanical testing is to analyze the strength, durability, stability to EIF dynamic type (dynamic testing). In this paper, we analyze the possibilities of reproducing targets and conditions for dynamic tests by computer simulation, accepted assumptions and simplifications, and used computational technologies. The experience of simulation of dynamic testing of the bearing (mechanical) structure of a precision reflector of the antenna for ground satellite communication systems is considered.

2. Statement of the problem

The object of the research is the test methods for mechanical EIF of dynamic nature (dynamic tests). The subject of study is the possibility of fully or partially reproducing the conditions, processes and phenomena of dynamic tests by computer simulation using standard (documented) tools and instruments of modern industrial CAE systems, the main result of which is detailed information on the stress-strain state (SSS) of the structure. The use of such information without the involvement of author’s algorithms and unique software provides the versatility and applicability of the results, conclusions and recommendations for a wide spectrum of users. The statement of the problem includes: a) an analysis of the possibilities of taking into account the features of the structures of the objects under test and the test technology when carrying out a computational experiment; b) the development of methods for computational experiments (simulation of dynamic tests); c) practical implementation of the technique on the example of computer simulation of dynamic testing of the bearing (mechanical) design of a precision reflector of the antenna for ground-based satellite communication systems.

3. The possibility of taking into account design features and test technology

When creating a numerical model of large-scaled structures, there are unavoidable simplifications and neglect of the “unimportant” geometric and structural features due to the problem of the model dimension and the limited computational resources available. Model dimension, as a rule, grows exponentially as the structure becomes more complex and its features are taken into account. In many cases, due to limited computational resources for structurally complex structures, the following model simplifications are unavoidable: only the main characteristics that determine the dynamic behavior of structures, namely, the spatial distributions of stiffness and masses of their main components and elements, the damping properties of materials, remain relevant to the real object. At the same time, connections of parts and elements are extremely simplified: the number and design features of connections, as a rule, are such that their consideration leads to an unacceptable dimension of the model. In this case, of course, the possibility of taking into account the damping abilities of connections is lost.

Obviously, the use of a simplified model reduces the accuracy and reliability of the estimated SSS. However, it is fundamentally important to emphasize this in relation to the following question: is the
decrease in the accuracy and validity of the calculated SSS the only or the main factor that impedes the replacement of mechanical tests of full-scale structures by their computer simulation?

In accordance with the current regulatory documents [4], the full range of structural responses to the effects of EIF is described by three properties:

- stability to EIF – the property of the object to keep a healthy state during and after exposure of a certain EIF on the object during the entire service life within the specified values;
- strength to EIF – the property of the object to keep a healthy state after exposure of a certain EIF on it within the specified values;
- resistance to EIF – the property of the object to keep a healthy state during exposure of a certain EIF on it within the specified values.

Thus, the property of stability to EIF takes into account the processes of degradation of the structure during the entire service life, initiated by the EIF. The property of strength to the EIF takes into account the damage, residual effects and effects arising because of the direct action of the EIF and remaining after its termination. The property of resistance to EIF reflects the mechanical phenomena and processes that emerging and flowing in the structure directly during the impact of the EIF. Obviously, if stability to EIF is ensured, then all the more strength and stability to EIF are ensured. Strength to EIF means simultaneously to resistance to EIF. Let us further consider the possibilities of analyzing stability, strength and resistance to EIF by computer simulation.

Computational analysis of stability requires simulation the process of damage accumulation after the termination of the EIF, the pattern of which in its most general form is described by generalized characteristics reflecting a decrease of the stiffness of the damaged material. In this case, the energy dissipation for the damaged material is defined as

\[ G_e = \int_0^{u_{ef}} \sigma_e du_e \]

where \( \sigma_e \) is equivalent stresses; \( u_e \) is equivalent displacements; \( u_{ef} \) are equivalent displacements for damaged material with reduced stiffness. These generalized characteristics are set in the range from 0 (intact material without a decrease in stiffness) to 1 (completely damaged material with zero stiffness). The high sensitivity of the result to the choice of these characteristics is obvious, which, in turn, requires theoretical substantiation and experimental evaluation. In principle, such information can be obtained for given loading conditions, but these data are not available when developing new designs. This does not allow us to consider the results of modeling damage accumulation as reliable and dramatically reduces the possibilities of computational analysis of stability to EIF.

Analysis of strength to EIF involves long tests. For example, “if it is necessary to determine the ability of a product to withstand the cumulative effects of vibration exposure, for example, fatigue, mechanical deformation etc., the test should be long enough to ensure the required number of load cycles. A number of load cycles of 10^7 is usually considered sufficient” [5]. Along with the accumulation of damage in structural materials during prolonged action of dynamic EIF, connections can be damaged. This cannot be taken into account due to simplified design in the development of a numerical model.

Computational analysis of stability to EIF is reduced to the verification of operability on the basis of current calculated values of stresses and strains. It does not imply the application of hypotheses and damage accumulation models and taking into account effects that are remote in time.

Thus, the computer simulation of resistance to EIF, which is reduced only to the analysis of SSS, is the most informative and suitable for decision-making. The results of damage accumulation modeling (analysis of strength and stability to EIF), especially for long periods of time (stability to EIF) are much less reliable due to the use of insufficiently specified models of damage processes and simplifications of the numerical model.
As for the conditions of fixing and loading of full-scale objects during mechanical tests, they can be reproduced with a computer simulation with a high level of accuracy and are not a factor reducing the accuracy and reliability of the results.

Let us further consider the methodological aspects of computer simulation of resistance to the main types of EIF dynamic nature.

4. Methodical support of computational experiments

The most frequently considered types of dynamic EIF are sinusoidal vibration, linear acceleration, acoustic noise, mechanical single and multiple shocks. The results of computer simulation of the structures behavior under the action of dynamic EIF substantially depend on the possibility of taking into account their damping abilities. Let us consider these possibilities in the numerical (finite-element) solution of the dynamics problems in the environment of the CAE-system ANSYS Workbench.

The resolving system of equations of motion is

$$[M]\ddot{u}(t) + [C]\dot{u}(t) + [K]u(t) = \{F(t)\}$$

where \([M], [C], [K]\) are, respectively, the mass, damping and stiffness matrices of the finite element model; \({\ddot{u}(t)}, {\dot{u}(t)}, {u(t)}\) are respectively the vectors of nodal accelerations, velocities and displacements as a function of time \(t\); \({F(t)}\) is the vector of nodal forces.

In general, the damping matrix is defined as [6]

$$[C] = \alpha[M] + \beta[K] + \sum_{j=1}^{N_{mat}} \beta_j[K_j] + \beta_c[K] + \sum_{k=1}^{N_{ele}} [C_k]$$

where \(\alpha, \beta\) are the proportionality coefficients of mass and stiffness, respectively, in the Rayleigh proportional damping model ([\(C]\) = \(\alpha[M] + \beta[K]\)); \(\beta_j\) is a constant factor to the stiffness matrix \([K_j]\) of the \(j\)-th material \((j = 1, N_{mat})\); \(\beta_c = \zeta(\pi f)\) is the variable factor to the stiffness matrix to ensure the independence of the degree of damping \(\zeta\) from the oscillation frequency \(f\); \([C_k]\) is the frequency-dependent damping matrix; \([C_k]\) is the damping matrix of the \(k\)-th element \((k = 1, N_{ele})\); \(N_{ele}\) is the number of elements that have their own damping matrix.

The use of one or another component of the damping matrix (3) depends on the type of the problem being solved and on the information support of the calculation (availability of information on the damping properties of materials and structures). The type of problem to be solved, in turn, is determined by the nature and method of describing the EIF.

There are known explicit and implicit statements of dynamic problems, differing in the way of integrating the equations of motion. The choice of statement is determined primarily by the physical essence of the problem and the intensity of the deformation processes under dynamic loading. The characteristics of EIF during testing are such that in most cases, preference should be given to methods of implicit dynamics.

With frequency independent EIF (linear acceleration – maximum linear acceleration, mechanical shock – peak shock acceleration and its duration), transient analysis is performed by complete solving the dynamic equations (2) by time integrating with the Newmark method with the search for equilibrium at each moment of time. The result of the analysis is the response of the system to an impact that changes over time.

In the case of EIF, specified in a certain frequency range (acoustic noise – the amplitude of the sound pressure level and frequency range of its action, sinusoidal vibration – the amplitude of the accelerations of sinusoidal vibration and frequency range \([f_{\text{min}}, f_{\text{max}}]\) of its action) the vector of nodal forces takes the form

$$\{F(t)\} = \{F_0\left(\cos(\omega t + \varphi) + i\sin(\omega t + \varphi)\right)\}$$

where \(\omega\) is the circular frequency; \(\varphi\) is the phase angle of the loading function; \(i\) – imaginary unit.
In the harmonic analysis the equations of motion (2)-(4) by the Eigen mode expansion method (modes superposition) are resolved with respect to displacements as functions of frequency. The main result of the solution is the amplitude-frequency response – the dependencies of the quantities of interest (stresses, strains) on the frequency of exposure.

There are some limitations on how to set the damping characteristics depending on the type of problems being solved. Thus, the use of the coefficient $\alpha$ in the Rayleigh damping model can lead to unsatisfactory results in case of the inclusion of concentrated added masses in the model; the use of the coefficient $\beta$ is undesirable in nonlinear problems; setting the damping using the frequency-dependent matrix $[C_\zeta]$ is possible only for harmonic analysis in the modes superposition way [6] ... An important issue is the information availability of damping characteristics of the equation (3): when developing structures that do not have close analogues, or using new materials, it is difficult to obtain the values of these characteristics.

In solving applied problems, we will proceed from the following considerations. It is well known that for most materials and structures, the contribution of internal friction in materials to the overall damping properties of an object is substantially less than the friction losses in the joints of parts (structural hysteresis) [7]. For example, the damping ratio of polymer composite material (PCM) according to experimental data [8] is 0.0041...0.0977, and structures made of such materials – 0.02369...0.16404 [9]. For structures with a large number of connections, tenfold increase in damping is possible compared with whole or welded structures [10]. However, it was noted above that when developing a numerical model, the connections are extremely simplified due to the dimension problem. Then the following approach is justified: according to the literature data [7, 8, etc.,] one should accept the scatter interval of the damping ratio $\zeta$ for structures of similar material and similar structural complexity. Further, based on the adopted values of $\zeta$, one can determine the parameters $\alpha$, $\beta$ or $\beta_c$ in equation (3). In this case, the results of solving problems of transient analysis or harmonic analysis will acquire an interval character.

Actually solving problems is carried out in the following sequence.

1) For a finite element model fixed in accordance with the test regulations, a calculation of the static stress state is performed under its own weight.

2) A modal analysis of the structure is carried out in prestressed states due to gravity (its own weight). When analyzing transients, the required number of modes is chosen from the condition of participation in free oscillations of at least 90% of the structure mass, but in any case at least three modes are accepted. With harmonic analysis, all modes are searched in the frequency range from $f_{\text{min}}$ to 1.5$f_{\text{max}}$.

3) In the harmonic analysis, a computational analysis of the response to the harmonic effect by the eigenmode expansion method is performed and the amplitude-frequency response of the resulting values is plotted.

4) In the analysis of transients, the minimum period of free oscillations $T_{\text{min}}$ is determined, corresponding to the highest mode found as a result of the modal analysis.

5) The maximum allowed integration step of the equations of dynamics is determined as $\Delta t = T_{\text{min}} / 20$.

6) The dynamics equations are integrated over the time interval of interest with a time step not exceeding $\Delta t$ (the number of subintervals should be at least 20), and the time dependencies and maximum values of the stress state characteristics are determined.

5. Simulation of dynamic tests of the parabolic antenna reflector design

Let us consider as an example of computer simulation of dynamic tests the results of computer simulation of the deformation of a large-scaled structure (diameter 10 m) of a precision reflector of a parabolic antenna for ground-based satellite communication systems (Figure 1). The mirror consists of separate segments, the cross section of which is formed by two layers of PCM and one layer of foam. Each segment, independently of the others, is mounted on a spatial beam skeleton, the elements of which (pipes) are made of unidirectional PCM.
The fixing of the finite element model is carried out at three points, corresponding to the conditions of fastening the structure to the hub (Figure 2). The analysis is performed for the characteristic spatial positions of the antenna: (a) – the focal axis is directed towards the horizon and parallel to the earth surface; (b) – the focal axis is inclined at an angle of 45° relative to the earth surface; (c) – the focal axis is directed toward the zenith, the angle between the focal axis and the earth surface is 90° (Figure 3). Accounting for the effect of its own weight, evenly distributed throughout the volume of the structure, is carried out by applying the gravity acceleration $G$. 

In accordance with the test regulations for equipment that has several operating positions, a change in position is considered as a change in the direction of exposure to mechanical factors. In this
connection, the fixed position of the model is used (Figure 1), and the values of the projections \( G_x, G_y, G_z \) of the gravity acceleration \( G \), the projections of linear acceleration, acceleration of sinusoidal vibration, peak shock acceleration, sound pressure are determined taking into account the position of the structure relative to the axes of the Cartesian coordinate system (Figure 3). Consideration of possible combinations allowed to justify nine design load cases.

Figures 4-6 show typical results of the calculations performed.

**Figure 4.** Amplitude-frequency response of normal stresses in the antenna mirror.

**Figure 5.** The equivalent stress field in the mirror under the action of a mechanical single shock.
Figure 6. The equivalent stress field in the skeleton under the action of a mechanical single shock.

The performed series of computational experiments is a computer simulation of the full range of dynamic structural tests in accordance with state and industry regulatory documents. As a result, confirmation of the compliance of conceptual and schematic solutions with technical requirements was obtained.

6. Conclusion

Computer simulation of dynamic tests of mechanical structures is an important tool for detecting and eliminating fundamental errors in their design, which can significantly increase the chance of successful implementation of real full-scale tests. In addition, it can be considered as one of the verification elements of their compliance with technical requirements in the verification process. The degree of proof of the level of conformity for each technical object is individual and is determined both by the simplifications of the structure when developing its numerical model and by how accurately the test regulations can be reproduced during their computer simulation. In any case, the simulation of testing provides additional arguments for making decisions in the process of verification of a technical object.

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