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Расчётно-экспериментальные исследования динамических характеристик макета рамы телескопа космического аппарата

А. А. Иголкин, А. И. Сафин*, А. В. Кузнецов

Самарский университет
Российская Федерация, 443086, г. Самара, ул. Московское шоссе, 34
*E-mail: safin@ssau.ru

В статье представлено расчётно-экспериментальное исследование динамических характеристик макета рамы телескопа космического аппарата. Основное внимание уделено методике проведения вибродинамических испытаний с использованием трёхкомпонентного лазерного виброметра и созданию конечно-элементной модели исследуемого макета. Для анализа динамики конструкции определены основные критерии, такие как модальные параметры, валидация модели и гармонический анализ. Особое внимание уделяется влиянию преобразования экспериментальных данных на точность расчёта критерия модальной достоверности. Исследован макет рамы телескопа, представляющий собой ферменную конструкцию, закреплённую на пружинах. Испытания проводились путём приложения случайного воздействия типа «белый шум». Получены динамические характеристики конструкции, включая собственную частоту колебаний, которая составила 93,7 Гц. Экспериментальные данные сравнивались с результатами конечно-элементного моделирования, показавшими значительное расхождение между ними, особенно в области собственных частот. Это свидетельствует о необходимости корректировки конечно-элементной модели. Рассмотрены различные критерии оценки соответствия расчётных и экспериментальных моделей, такие как координатный критерий модальной достоверности (COMAC), критерий модальной достоверности (MAC), взаимный критерий гарантии (CSAC) и взаимный коэффициент пропорциональности (CSF). Эти критерии помогают оценить степень совпадения форм колебаний и частотных характеристик. Проведён анализ влияния преобразований экспериментальных данных в разные единицы измерения на результаты расчётов этих критериев. Сделан вывод о том, что текущая расчётная модель требует доработки и уточнения параметров для достижения лучшего соответствия с реальностью.

Ключевые слова: модальные параметры, конечно-элементная модель, валидация, гармонический анализ, критерии модельной достоверности, амплитудно частотные характеристики.

Calculation and experimental study of the dynamic characteristics of the spacecraft telescope frame mockup

A. A. Igolkin, A. I. Safin*, A. V. Kuznetsov

Samara University
34, Moskovskoe Shosse Str., Samara, 443086, Russian Federation
*E-mail: safin@ssau.ru

The article presents a computational and experimental study of the dynamic characteristics of a spacecraft telescope frame mock-up. The main attention is paid to the methodology of vibrodynamic tests using a three-component laser vibrometer and the creation of a finite element model of the mock-up under study. To analyze the dynamics of the structure, the main criteria such as modal parameters, model validation and harmonic analysis are defined. Particular attention is paid to the effect of experimental data transformation on the accuracy of calculating the modal assurance criterion. The research investigates telescope frame mock-up, which is a truss structure fixed on springs. The tests were carried out by applying a random impact of the "white noise" type. The dynamic characteristics of the structure were obtained, including the natural frequency of oscillations, which was 93.7 Hz. The experimental data were compared with the results of finite element modeling, which showed a significant discrepancy between them, especially in the area of natural frequencies. This indicates the need to adjust the finite element model. Various criteria for assessing the compliance of calculated and experimental models are considered, such as the coordinate modal assurance criterion (COMAC), the modal assurance criterion (MAC), the cross signature assurance criterion (CSAC) and the cross signature scale factor (CSF). These criteria help to assess the degree of coincidence of vibration modes and frequency characteristics. An analysis of the effect of transforming experimental data into different units of measurement on the results of calculating these criteria is carried out.

It is concluded that the current calculation model requires revision and clarification of parameters to achieve better compliance with reality.

Keywords: modal parameters, finite element model, validation, harmonic analysis, criterion of model reliability, amplitude-frequency characteristic.

Introduction

In the current trend of testing the vibration strength of spacecraft (SC) structures using its first flight model as the object of study, and accordingly using computational and experimental methods, based on the results of experimental testing, the task of correcting the finite element model (FEM) is becoming increasingly relevant [1–8]. At the same time, non-contact methods for obtaining dynamic characteristics are becoming widespread, the undoubted advantage of which is the possibility of testing very small and light structures [9; 10]. Due to the test results, FEM correction can be carried out using a direct or iterative method. Also, methods of FEM correction can be classified according to the use of frequency and modal characteristics of the object studied [11; 12]. As is known, the use of frequency response functions (FRF) has advantages over the use of modal data, since the latter are usually extracted from a limited number of points around the resonant peaks on the FRF curves with inherent numerical errors, while the FRF contains information from the full frequency spectrum. Each of the methods is characterized by calculating its own criteria. However, the use of various criteria, such as the coordinate modal assurance criterion (COMAC) with the modal assurance criterion (MAC) [equation (1)] for modal data and the criteria for frequency data – the cross signature assurance criterion (CSAC) [equation (2)] and the cross signature scale factor (CSF) [equation (3)], comes down to obtaining a numerical value or a table of values ranging from 0 to 1. The article presents an example of calculating some of the specified criteria, considering the features of processing experimental data and the influence of errors in comparison to the calculated and experimental grids.

The correlation analysis of the frequency response function between pairs at each frequency point is assessed in terms of the cross signature assurance criterion (CSAC) and the cross signature scale factor (CSF). CSAC is a measure of the shape correlation between the experimental and analytical frequency responses, ranging from 0 to 1 [Equation (2)]. Meanwhile, CSF is a measure of the difference in amplitude between the measured and calculated responses, ranging from 0 to 1 [Equation (3)]. In general, these two frequency response function (FRF) correlation functions can be known as cross-signature correlation (CSC) functions. They are usually expressed in percent (%) for easier interpretation.

$$MAC = \frac{\left| \{\Psi_X\}_i^H \times \{\Psi_A\}_j \right|^2}{\left(\{\Psi_A\}_j^H \times \{\Psi_A\}_j \right) \times \left(\{\Psi_X\}_i^H \times \{\Psi_X\}_i \right)}, \quad (1)$$

where $\{\Psi_X\}_i$ – experimental frequency form; $\{\Psi_A\}_j$ – calculated frequency form.

$$CSAC(\omega_\kappa) = \frac{\left| A_M^H(\omega_\kappa) \times A_P(\omega_\kappa) \right|^2}{\left(A_M^H(\omega_\kappa) \times A_M(\omega_\kappa) \right) \times \left(A_P^H(\omega_\kappa) \times A_P(\omega_\kappa) \right)}, k = 1, 2, .., N_f, \quad (2)$$

$$CSF(\omega_\kappa) = \frac{\left| A_M^H(\omega_\kappa) \times A_P(\omega_\kappa) \right|^2}{\left(A_M^H(\omega_\kappa) \times A_M(\omega_\kappa) \right) + \left(A_P^H(\omega_\kappa) \times A_P(\omega_\kappa) \right)}, k = 1, 2, .., N_f, \quad (3)$$

where A_P – calculated values of FRF vibration displacements; A_M – experimental values of FRF vibration displacements; N_f – natural frequency (tone number).

Experimental and calculated research

The object of the study is a model of the telescope frame of the remote sensing spacecraft (RS SC) and is a truss structure (Fig. 1). To conduct the tests, the structure was suspended on springs with stiffnesses of 770 and 730 N/m. The disturbance was applied using a vibration pulsator with a built-in force sensor that made it possible to obtain data on the magnitude of the disturbance. The structure was loaded in a random direction using random "white" noise.

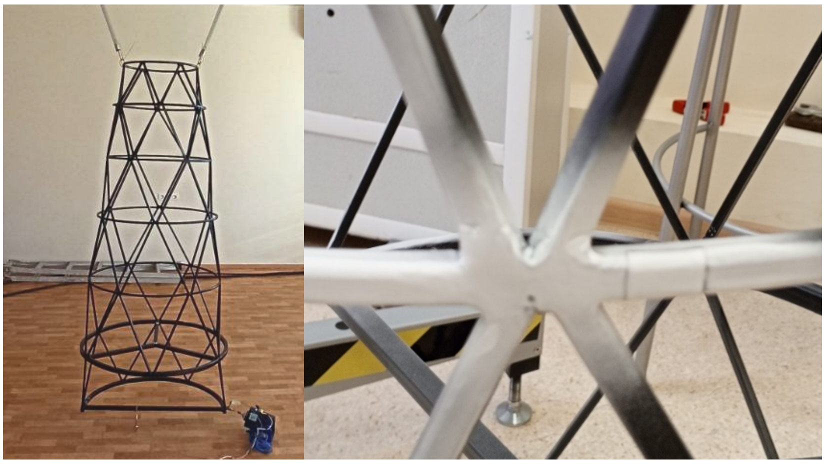

Рис. 1. Макет рамы телескопа на подвесках и закраска конструкции для выделения места снятия данных

Fig. 1. Model of the telescope frame on suspensions and painting of the structure to highlight the data collection location

The study of the dynamic characteristics of the telescope frame model design was performed using a three-component laser scanning vibrometer Polytec PSV 400-3D. The expected locations of the laser beam impact were painted white. Since the design of the model has got a complex spatial shape (Fig. 1), obtaining dynamic characteristics is possible only for 1/4 of the design in one measurement without moving the measuring devices of the laser vibrometer. Conducting subsequent experimental studies while moving the measuring devices allows to obtain dynamic characteristics measured for points in the rest of the structure. Initial analysis showed that the "junction" points of the experimental grids of the structure may be in different phases (Fig. 2). This feature is assumed to be associated precisely with the type of the disturbance function, since due to "white noise" type of disturbance, the phase value is random. The solution of this problem is not intended within the scope of this article.

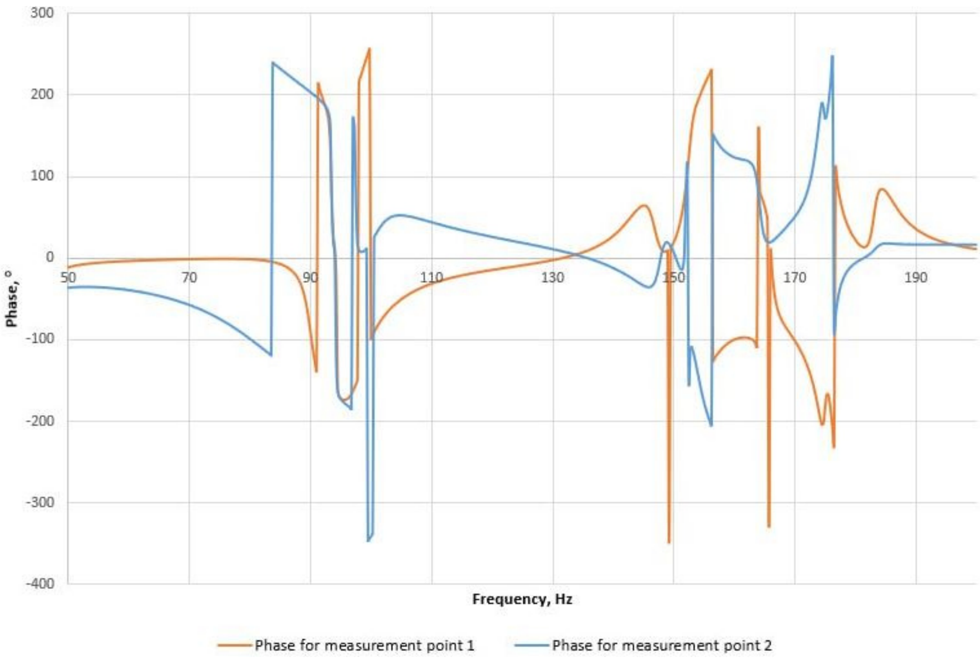

Рис. 2. Фазы совпадающих точек замера двух соседних замеров

Fig. 2. Phases of coinciding measurement points of two adjacent measurements

Using a laser vibrometer as a measuring instrument allows to obtain vibration velocities at measurement points as direct results. In specialized software, vibration velocities can be converted into vibration accelerations and vibration displacements [13]. In addition, the presence of a force sensor also permits to calculate frequency characteristics in the form of transfer functions. A primary analysis of the specified characteristics allows to draw a conclusion about the location of the natural frequencies. Therefore, the curves of the root-mean-square value of the vibration displacement amplitudes in all directions for all measurement points show the first frequency of natural oscillations at 93.7 Hz (Fig. 3). Transfer functions afford the opportunity to calculate modal parameters, namely natural modes and frequencies of oscillations [14; 15]. Since the results of the experiment can be represented in the form of three different dimensions: vibration acceleration, vibration velocity and vibration displacement (in general, for different equipment, one of the specified characteristics is taken directly from the measuring instrument, and the other two are calculated), then the calculation of natural modes is also possible when using any of the characteristics as the initial data. In this case, the question arises of the error occurring when transforming quantities.

The finite element model of the frame layout of the remote sensing spacecraft telescope was constructed using beam elements and additional connecting elements with rigidity and damping characteristics.

The results of calculations and vibration tests showed that the first and second natural frequencies of the calculation model are close to the experimental values of the vibration frequencies of the first and second tones of the telescope frame model. Fig. 4 demonstrates the values of the MAC criterion while obtaining vibration modes from FRF based on vibration displacements. The analysis of the obtained data reveals poor correspondence between the calculated and experimental vibration modes and the need to correct the finite element model, as well as an insignificant difference in the calculated criteria from the transformation of experimental data into different units of measurement.

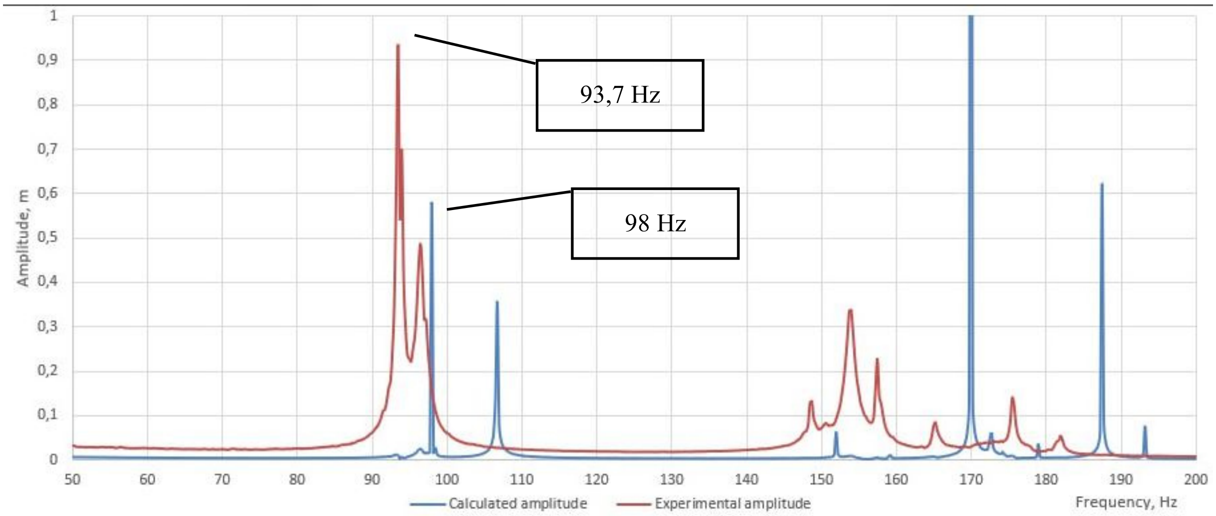

Рис. 3. Среднеквадратичные значения амплитуд виброперемещений
по всем направлениям для всех точек замеров

Fig. 3. Root-mean-square values of vibration displacement amplitudes
all directions for all measurement points

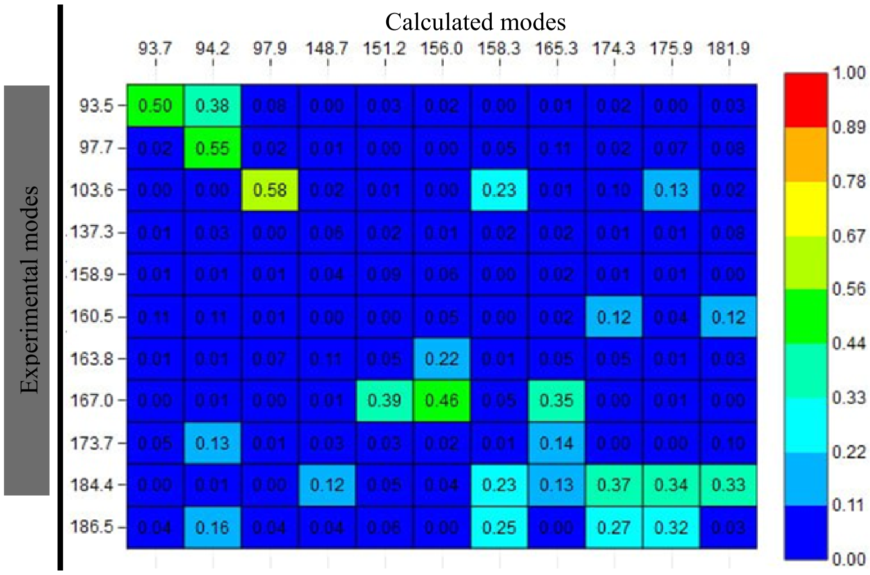

Рис. 4. Значения критерия MAC при получении экспериментальных
форм колебаний от FRF по виброперемещениям

Fig. 4. MAC criterion values when obtaining experimental vibration modes
from FRF based on vibration displacements

The COMAC values (Table 1) indicate that the spatial correlation of the experimental and calculated pairs of nodes is very low; this ratio does not indicate a discrepancy between the calculated experimental grid in space, but speaks of the different nature of the vibration modes in the experimental and corresponding calculated points. This is also confirmed by the fact that the experimental grid nodes can be moved to the corresponding calculation node without changing the procedure and the result of the COMAC calculation. Intermediate transformation of experimental data into different units of measurement does not affect the COMAC values.

A special feature of the CSAC calculation is that it is necessary to compare complex characteristics in accordance with the positive and negative directions in degrees of freedom (three translational and three rotational), which in general gives 12 different criteria. The available experimental and calculated data allow to obtain 3 CSAC criteria for the positive direction during translational motion relative to each of the three axes of the global coordinate system.

Table 1

COMAC criterion values

Node numbers calculated	Node numbers experimental	COMAC_X	COMAC_Y	COMAC_Z
290	40	0.1958	0.0720	0.2889
1971	44	0.1307	0.1043	0.0776
2014	46	0.1958	0.1039	0.2852
2262	34	0.0745	0.1285	0.0510
2636	48	0.0783	0.1071	0.0388
2810	41	0.0739	0.1701	0.0414
1112009	50	0.3968	0.1229	0.2258
1112068	35	0.1067	0.1174	0.0801
1112141	47	0.2412	0.0529	0.0783
1112211	26	0.1467	0.1729	0.1058
1112271	39	0.1165	0.0495	0.1674
1112280	23	0.1283	0.0812	0.1367

Fig. 5 presents both the obtained values of the specified criterion and the arithmetic mean value.

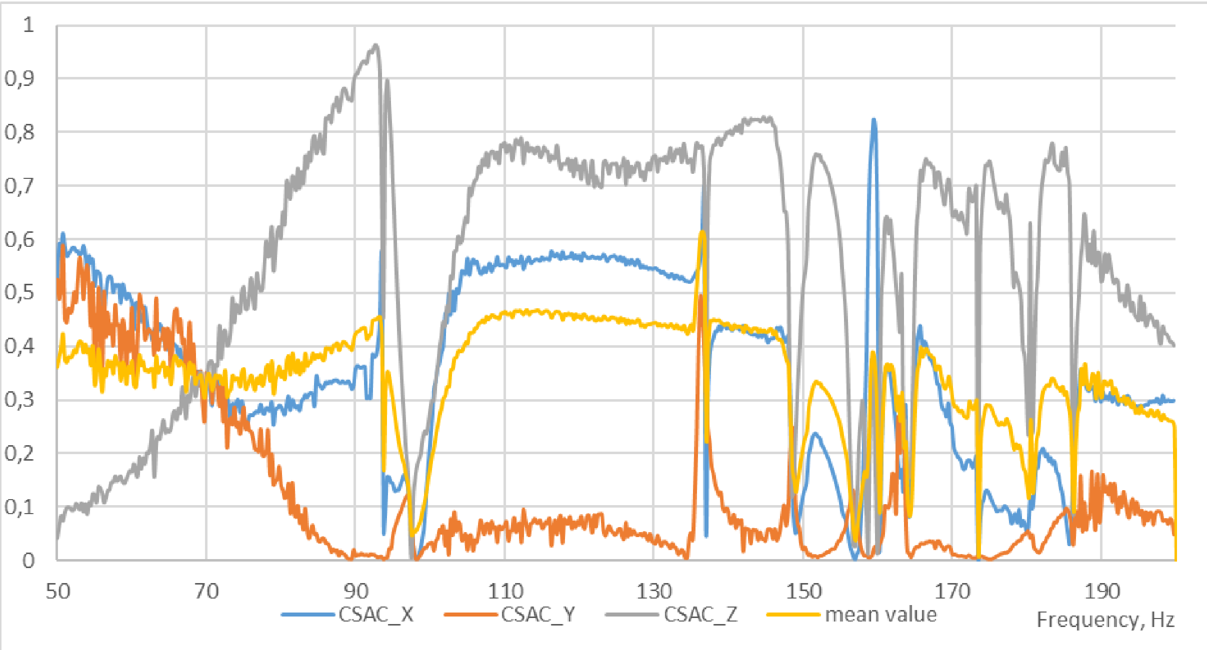

Рис. 5. Значения критерия CSAC по FRF виброперемещениям

Fig. 5. Values of the CSAC criterion for FRF vibration displacements

Analysis of the obtained data shows that the results of the calculation model do not correspond to the dynamics of the structure along the Y axis to a greater extent than along other axes. In the region of natural frequencies, the calculation model gives a complete discrepancy with the experiment, and in the frequency range from 100 to 145 Hz it most corresponds to the behavior of the loaded structure along the Z and X axes.

Similar to the CSAC criterion, CSF also considers the axis and direction, which affects the nature of the CSF curve. However, this criterion characterizes compliance with the amplitude of oscillations, which in turn leads to dependence on the applied forces. Since the previous calculation of CSAC showed a discrepancy between the calculated and experimental models, the calculation of the CSF criterion cannot be reliable. Figure 6 demonstrates the similarity in nature of the CSAC and CSF criteria for the same axis (the Z axis is taken as an example), as well as the dependence of the CSF criterion on the value of the applied efforts.

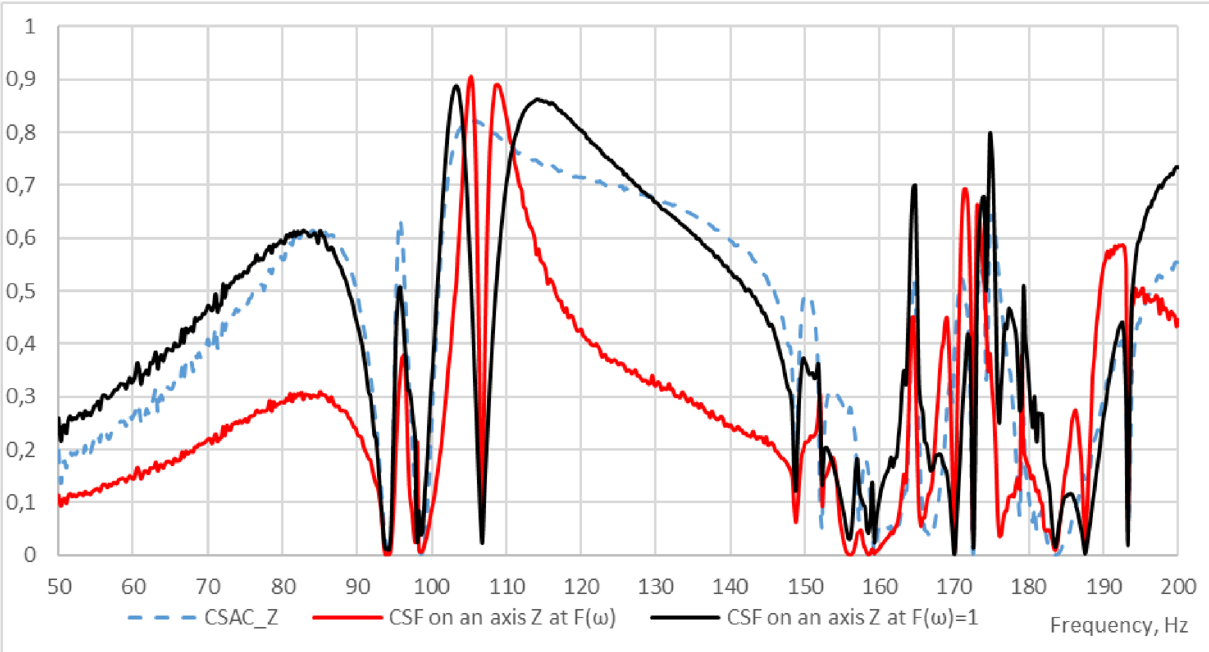

Рис. 6. Результаты расчёта критерия CSAC для оси Z; CSF при нагрузке в виде зависимости силы от частоты F(ω), соответствующей экспериментальным данным; CSF при нагрузке в виде единичной силы в рассматриваемом диапазоне частот

Fig. 6. Results of calculating the CSAC criterion for the Z axis; CSF under load in the form of a dependence of force on frequency F(ω), corresponding to experimental data; CSF under load in the form of a unit force in the frequency range under consideration

For a quantitative comparison of the results of the ratio of calculated and experimental data, we will reduce the MAC criterion to an average value in percentage terms using formula (4) and CSF using formula (5):

$$MAC_{\%} = \left(\frac{\sum_{i=1}^{n} MAC_i}{n} \right) \times 100\ \%, \tag{4}$$

where n – natural frequencies,

$$CSF_{\%} = \left(\frac{\sum_{i=1}^{n} CSF_i}{n} \right) \times 100\ \%, \tag{5}$$

where n – discrete frequencies of the entire measurement range.

The obtained values of $MAC_{avg.}$ = 29.5%, $CSF_{avg.}$ = 34.8% indicate that the correlation of the experimental and calculated forms for resonant frequencies in the system under consideration is lower than the correlation of the experimental and calculated frequency characteristics in the entire frequency range under consideration.

Conclusion

The conducted research has showed the importance of using modern methods of vibrodynamic testing and creating accurate finite element models for analyzing the dynamic characteristics of spacecraft structures and their components. The presented methodologies allow to obtain detailed information about the behavior of telescope frame models under the influence of external loads, which is critically important for the design of reliable and durable spacecraft.

Significant discrepancies have been found between the calculated and experimental data, especially in the area of natural frequencies, which emphasizes the need for careful calibration and adjustment of the finite element model. The application of various conformity assessment criteria such as COMAC, MAC, CSAC and CSF helps to identify weaknesses in the model and identify ways to improve it.

Further research should focus on selecting optimal variable parameters and establishing the boundaries of their values to carry out an effective model correction procedure. Only in this way can we achieve high accuracy in predicting the behavior of real structures under operating conditions and ensure the reliability and safety of space missions.

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Иголкин Александр Алексеевич – доктор технических наук, доцент, профессор кафедры автоматических систем энергетических установок; Самарский университет. E-mail: igolkin@ssau.ru. https://orcid.org/0000-0001-7411-0534

Сафин Артур Ильгизарович – кандидат технических наук, доцент кафедры автоматических систем энергетических установок; Самарский университет. E-mail: safin@ssau.ru. https://orcid.org/0000-0003-0936-4364

Кузнецов Александр Владимирович – инженер НИИ-201; Самарский университет. E-mail: al.vl.kuznetsov@mail.ru. https://orcid.org/0000-0001-5485-427X

Igolkin Alexandr Alekseevich – Dr. Sc. (Engineering), Professor; Samara National Research University. E-mail: igolkin@ssau.ru. https://orcid.org/0000-0001-7411-0534

Safiv Artur Ilgizarovich – Cand. Sc. (Engineering), Associate Professor; Samara National Research University. E-mail: safin@ssau.ru. https://orcid.org/0000-0003-0936-4364

Kuznetsov Alexandr Vladimirovich – engineer; Samara National Research University. E-mail: al.vl.kuznetsov@mail.ru. https://orcid.org/0000-0001-5485-427X

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