Experimental Study of Vibrations of Cross-Rod Spatial Structures

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The issue of choosing methods for excitation of free and forced vibrations is being investigated, equipment for recording and recording vibrations is selected, and a layout of vibration sensors and sources of excitation of free and forced vibrations is being developed. Natural vertical oscillations of the structure model were caused by removing it from the state of equilibrium by concentrated loads applied in the middle and in a quarter of the span with their subsequent removal.

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This article explores a technique for studying the dynamic characteristics of cross-rod spatial structures (CRSS) using small-scale models, including the developed nodal connection of spatial frame rods, protected by copyright. The use of a nodal connection makes it possible to regulate the construction lifting of large-span structures, increases their strength and reliability. The developed nodal connection of the structure can be used for any spatial frames of buildings and structures and is especially effective for the frames of buildings erected in areas of high seismicity.

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The test results and their analysis are analyzed. The elements of experimental models at all stages of loading worked in the elastic stage. The tests carried out showed that the structure has sufficient strength, stability, rigidity and seismic resistance. On the basis of the results obtained, recommendations were made for their use in the calculation and design of CRSS for seismic regions.

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I. INTRODUCTION

Due to the variety of seismic actions and the specific features of the CRSS, the range of problems associated with their oscillations and dynamic calculation is very wide. From a seismic point of view, PSPKs are systems with distributed parameters and an infinite number of degrees of freedom. Vibrations of spatial structures are of a complex nature and are determined by the joint spatial displacements of nodes and rod elements of the CRSS [1].

The analysis of literary sources also showed that there is a significant discrepancy between the experimental and theoretical results obtained in the process of experimental studies on full-scale structures [2, 3, 4].

Therefore, despite the successes, in general, the problem of seismic resistance of the CRSS has not been resolved. To solve it, further theoretical and experimental studies are required. Carrying out full-scale studies of the seismic resistance of FPCS, especially with various design schemes, seems to be very laborious and expensive. Based on this, in this article an attempt is made to solve these problems in a more accessible way with the help of experimental studies on small-scale models. In this article, we study a technique for studying the dynamic characteristics of CRSS using small-scale models, including a newly developed nodal connection of rods of a spatial frame, protected by an author's certificate [5].

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II. METHOD

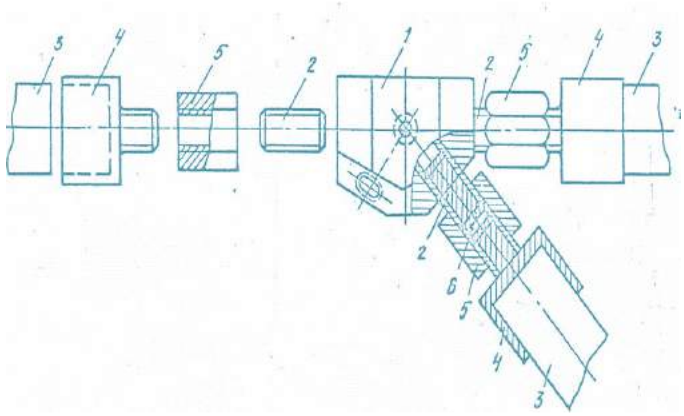

Fig. 1: Nodal Connection of the Rods of the Spatial Frame

2.1 Description of the Nodal Connection of the CRSS

The experimentally investigated nodal connection contains a nodal element 1 of a spatial frame with studs 2 freely fixed in it, to which rods 3 with rigidly fixed tips 4 are attached by means of a moving coupling 5 with a gap. The connection of the rod 3 with the nodal element 1 is carried out by moving the coupling 5 from the pin 2 to the threaded part of the tip 4, while the length of the rod in the axes of the nodal elements is regulated by the gap 6 between the pin and the tip, and the preliminary the tension is achieved by the depth of screwing the pin 2 into the threaded hole of the nodal element. The use of a nodal connection makes it possible to regulate the construction lifting of large-span structures, increases their strength and reliability. The developed nodal connection of the structure can be used for any spatial frames of buildings and structures and is especially effective for the frames of buildings erected in areas of high seismicity.

2.2 Creation of a Model Structure

New structures intended for construction in seismic areas are investigated not only for the effects of seismic loads, but also for the effects of conventional static loads.

In addition, the method for calculating structures for seismic regions adopted by the current standards assumes that after determining the seismic loads, the latter are applied statically to the structures. In experimental studies of CRSS, sometimes the dynamic load is replaced by a static one in order to identify, as a first approximation, the general nature and features of the stress-strain state of CRSS. Thus, static studies of structures for seismic regions are, on the one hand, of independent importance, and on the other hand, they serve as a kind of model for the work of the CRSS on seismic effects.

Taking into account the specifics of the impact on the structure of harmonic vibrations, which depend on external factors and, in particular, on the material of the model, for model imitation of metal rod structures, it was decided to make a model from metal rod and node elements.

The prerequisites underlying the constructive solution of the experimental model were the following:

- geometric similarity between the model and the real structure, achieved by the ratio of the lengths of the rods equal to 1/10;
- the similarity of the rigidity of the rods of the model and the real design achieved by using tubular rods of various diameters of 6.8 and 12 mm;
- the similarity of the nodal connection in the model and the real structure, achieved by using a single bolted connection, working on longitudinal tensile-compression forces.

Tests of the structure model for a static load were carried out in order to establish a qualitative and quantitative coincidence of the results of the actual stress-strain state with the results of an accurate calculation performed on a computer [6, 7].

During the experiment, the ambient air temperature was constant, which made it possible to measure vibrations of any direction with the same sensor (horizontal or vertical). The tests were carried out to make a decision on the possibility of using the experimental model for dynamic testing.

Oscillations of the structure model, both in the vertical and horizontal directions, were excited:

- instant removal of suspended loads;
- guying of the column heads with the calculated static load when it is instantly released;
- falling load;
- vibration motor, on the shaft, which was mounted with eccentrics.

Natural vertical oscillations of the structure model were caused by removing it from the state of equilibrium by concentrated loads applied in the middle and in a quarter of the span with their subsequent removal. The natural horizontal oscillations of the structure model were caused by a static load pulling the top of the columns with its instantaneous release. The load was released and the columns were pulled using a system of cables, and the mass of the load was 10–15% of the mass of the structure model under study.

The maximum number of revolutions developed by the vibrating machine used was 1800 revolutions per minute, which corresponded to the highest frequency of forced vibrations of the PSPK 30 Hz. At the maximum number of revolutions, the amplitude of the load created was 90 N. The eccentric load had a mass of 100 g. and fastened at a distance of 2.5 from the axis of rotation. The number of revolutions of the vibrator (the frequency of the studied oscillations) was regulated using an autotransformer introduced into the installation circuit of the vibrator. In this case, the inertial force was determined by the well-known formula:

$$P = 4\pi^2 m_{э l_э \omega}{}^2$$

Where $m_э$ is the mass of the eccentrics; $l_э$ is the eccentricity equal to 2.5 sm; ω - is the number of revolutions in 1 second. Note that the magnitude of the inertial force of the vibrating machine was chosen in such a way as to cause oscillations with amplitudes that could be recorded by an oscilloscope with sufficiently large magnifications and at the same time not cause nonlinear oscillations [8].

2.3 The Choice of Equipment

The choice of equipment for recording vibrations was made taking into account the possibility of recording waveforms in the frequency range from two to 30 Hz, and amplitudes from 1 to 100 microns and obtaining multipoint recording in movements to identify possible forms of vibrations. The following equipment was used during the tests:

1. A set of devices for measuring vibration of type K001, consisting of horizontal vibration sensors of type I001G, vertical vibration sensors of type I001B, a magnification regulator R001, integrating galvanometers of type M002 and a 14-channel light-beam oscilloscope of type POB-14. The frequency measurement range for the kit K 001 was 1.5-200 Hz. The permissible oscillation amplitude is up to 1000 microns.
2. Miniature seismic receivers SMV-30 of the "Firefly" type, used to control some experiments that exclude the influence of the mass of vibration sensors K001. They are converters of mechanical movements into electrical signals and are designed to register the vertical components of seismic waves. The range of measured frequencies is from 1 to 300 Hz, and the natural frequency of the device is 29 = 1 Hz, the diameter of the device is 29 mm, the length with a tip is 100 mm, the weight of the device without a tip is 100g.
3. In some rods of the design model, deformations were recorded by strain gauges with recording on the POB-14 oscilloscope via the V-ANCH-7M amplifier.

The square shape of the experimental models determined the installation location of the vibration sensors along the axes of the quarter, and the vibration machines in the center of the structure and the quarters of the spans.

Micro-vibrations of the base were excluded by the massiveness of the experimental stand and were controlled by a vibration sensor. By pre-installing the vibration sensors on the model, they were calibrated to determine the frequency and amplitude characteristics and to adjust the same phase of the vibration sensors necessary to determine the waveforms.

Vertical vibration sensors were installed on special round plates using 4 M6 bolts, and horizontal vibration sensors were installed on special angles using 4 M-6 bolts.

2.4 Calibration of a Set of Devices

Calibration of the set of instruments was carried out as follows:

1. Vibration sensors were installed on special calibrated stands that create vibration with the required frequency and amplitude. The vibration stand platform produced harmonic vibrations. The control of the frequency and amplitude of the oscillations was carried out with greater accuracy than the control of the tested devices.
2. Galvanometers used in conjunction with a set of instruments were installed in certain channels of the oscilloscope, and when measuring vibrations, galvanometers were installed, and the same channels of the oscilloscope.
3. The frequency and amplitude characteristics in the operating range of frequencies and amplitudes were removed, the values of the magnification coefficients were determined. Dynamic tests began with the installation of minimal eccentric loads on the vibrating machine and the creation of vibrations with a slow increase and decrease in the speed of the electric motor, regulated by an autotransformer in the frequency range from 1 to 30 Hz.

By visual observation on the oscilloscope screen, the resonant oscillation zones were determined and the recording scale and the speed of the photo paper were determined. In the zone of resonant revolutions of the fundamental tone, the attenuation of free vibrations was studied when the vibrating machine was switched off. Only mechanical devices were installed to measure vertical movements along the lower belt of the model. By changing the place of application of force or load (the source of excitation of free and forced oscillations), the nature of changes in dynamic parameters was established [9].

The frequency of free oscillations was determined both by the oscillograms of damped free and forced oscillations, and by the diagrams of resonant curves[10]. The values of the logarithmic decrement were determined by damped free oscillations, as well as by resonant curves [11].According to the amplitudes recorded simultaneously at 6 points, plots representing waveforms were constructed.

2.5 Determination of Dynamic Characteristics

The tests were carried out to identify the stress-strain state and dynamic parameters (periods, shapes, and decrement fluctuations) of the CRSS with various support options and structural schemes and to establish the influence of enclosing structures on the stress-strain state and dynamic characteristics. All waveforms recorded during dynamic tests were processed according to a single methodology. At each level of free oscillations, the most characteristic and stable section was selected, on which the dynamic parameters of the design model were determined. According to these values, taking into account the calibration data of the equipment, the movements of individual points of the model were determined, which made it possible to identify the forms of its oscillations.

The oscillograms represented a picture of oscillatory motion expanded in time. They were used to determine the frequencies and periods of oscillations, as well as the amplitudes of oscillations. To determine the oscillation amplitudes on an oscillogram, the distance between adjacent half-wave vertices was measured. Half of this distance is the amplitude. For the accuracy of determining the amplitude, the scale of recording the waveforms was of great importance, therefore, the maximum magnification of the regulator was used. When determining the oscillation period, the first two half-waves of the oscillogram were not taken into account, since they were influenced by various transients.

The rest of the waveform obeyed a general pattern and the oscillation periods were determined by it. On the oscillogram, the natural oscillation period of the structures is 0.2 and 0.16 s, respectively, hence the oscillation frequencies f = 1 / T turned out to be equal to 5 Hz and 6 Hz, respectively.

Recordings of free damped oscillations made by:

- at different stages and with different types of loads of the structure with a constant load and with different support options;
- various design schemes;
- various levels of dynamic stresses characterized by the magnitude of the broken load allowed us to obtain numerical values of the logarithmic decrement.

According to the recording of the oscillogram, the ratio of adjacent amplitudes and periods was found, the vibration attenuation coefficient K3 was determined.

$$K_3 = \delta / T$$

Where, δ is the natural logarithm of the ratio of adjacent amplitudes, called the logarithmic decrement of oscillations.T is the period of free oscillations.

The value of the coefficient for metal structures is usually recommended to be taken depending on the level of dynamic stresses at low loads of 0.01, and at high loads - 0.025. The amplitudes of movements in the center of the PSPC served as a generalized characteristic of the level of dynamic stresses of the structure, since the fluctuations of the PSPC during the breakage of the load occurred in the first form.

III. RESULTS AND DISCUSSIONS

According to the results of processing vibrograms of their own damped oscillations, the dependences of γ(a) of the loss coefficient on the amplitude of the oscillations (in the first form) in the center of the plate were found. According to the obtained oscillograms, the first 3 forms of natural vibrations of the structure were constructed. The amplitude - frequency characteristics of oscillations for individual points were also constructed. The frequencies, shapes and amplitudes of the natural oscillations of the unloaded model were also determined, as well as at a loading stage of 20% of the calculated one. Then a vibration motor was installed and forced vibrations were created at various stages of loading.

At the same time, the experimental results (the frequency and amplitude of the natural oscillations of the model) corresponding to different stages of loading with a constant load, in the presence of loads differ from each other by more than 20%, and the frequencies in the presence of loads are greater than in the absence of it.

This is due to the fact that loading practically does not affect the rigidity of the model. Loading caused an increase in mass, which, in turn, caused an increase in the values of the period of natural oscillations. Experimental studies show that with low-mass eccentrics, changes in frequencies and decrements of vibrations both at the beginning of the vibration machine and after some time of operation of the vibration machine occur slightly, only amplitudes increase.

With eccentrics of a larger mass, the oscillation frequencies noticeably decrease and the amplitudes and decrements of oscillations significantly increase. According to the results of processing the oscillograms of their own damped oscillations, the dependences of the loss coefficient γ(a) were foundfrom the amplitude of the oscillations in the center of the CRSS model. The arrangement of the curves in Fig.2 indicates that with increasing static stresses in the structure, the value of the inelastic resistance coefficient decreases.

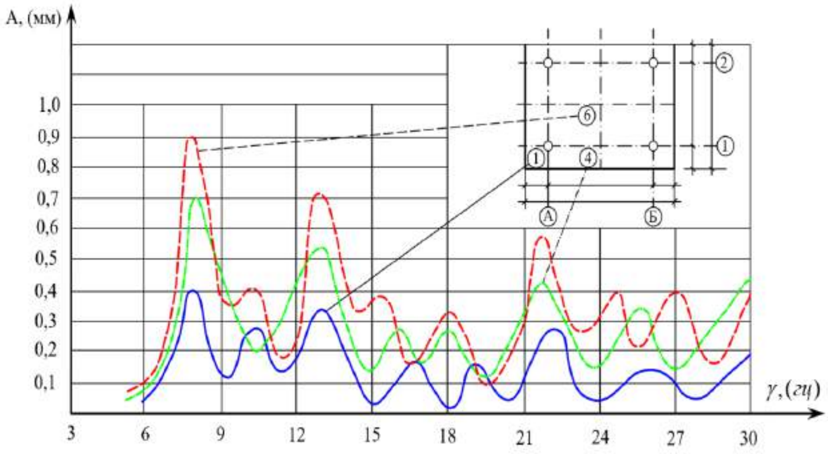

Fig. 2: Resonant Curves of Forced Oscillations of Various Nodal Points

It has been experimentally established that the coefficient γ at a low level of dynamic stresses can take a value less than that accepted in regulatory documents.It is characteristic that at a low level of dynamic stresses, the value of the loss coefficient (γ = 0.0065) for PSPC is 35% less than that accepted in regulatory documents.At the maximum level of dynamic stresses, the value of γ is equal to 0.018 for the same type of structures, which is 20% less than accepted in regulatory documents.This fact has a noun meaning, since we are talking about calculations of oscillations of repeatedly statically indeterminate systems in the resonant mode [12,13]. The results of tests for vertical seismic loads showed that 3 resonant zones were recorded on the oscillogram for the PSPC models with a smooth decrease in often forced vertical oscillations. With the growth of external uniformly distributed static and dynamic loads, there was a decrease in the frequencies of natural vertical vibrations and the dynamic stiffness of the PSPC, and their shapes did not change [14].

This is typical for systems in which the dissipation of oscillation energy is caused by an internal inelastic resistance [15,16]. Under the action of a horizontal load, a coating with columns in the first approximation can be considered as a system with one degree of freedom or with an infinite number of degrees of freedom. For example, for a system with one degree of freedom, comparing the values of frequencies can cancel the proximity of their values.

At all stages of loading, the structure worked elastically, without residual deformations after unloading. The forces in the rods increased in proportion to the increase in the inertial impact and the design load in the range up to 2700 Pa.From the evenly distributed load over the entire coating, the struts of the structure along the main diagonal were the most loaded. Under seismic impacts, the forces in these struts increased from 5 to 18%. The greatest tensile force from the 9-point seismic load was recorded in the rod of the upper belt above the support, the greatest compressive force from the 9-point seismic load was in the struts of the support zone.

As can be seen from Fig.3. When the constant load q = 1080 Pa and 2700 Pa, the graphs γ(a) have a horizontal increase in amplitudes and a sharp decrease in the values of γ in the regions of small amplitudes. In the center of the structure, the greatest force in the rods reached 825N. The greatest effort was in the rod directed towards the center of the structure along the main diagonal of the support pyramid. In the rods forming the base of the support pyramid and located above the braces, the forces are small-163 N.

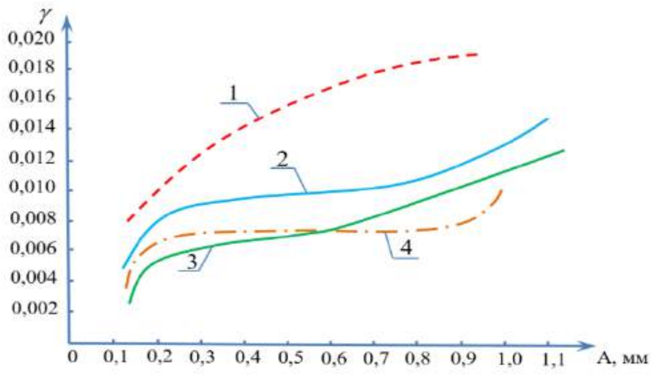

Fig. 3: Dependence γ(A) for Different Levels of Loading of the Model With a Constant Load: 1,2,3,4 - at a Load of 0.54; 1.08; 1.68; 2.7 kN/m2.

With the growth of the external uniformly distributed load and dynamic loads, there is a decrease in the frequencies of natural vertical vibrations and the dynamic stiffness of the PSPC while maintaining their constant shape.

The results of tests for vertical loads of the seismic type showed that the CRSS model, with a smooth decrease in the frequencies of forced vertical oscillations, three resonant zones are fixed on the oscillogram.

Experiments have also shown that the periods of proper vertical oscillations of experimental models are in the range of 0.06 - 0.207 sv depending on the type of models and the conditions of support. The nature of the variation in the oscillation amplitudes of individual points of the CRSS was revealed, gradually fading in time, and logarithmic decrements were determined for vertical oscillations, the value of which is not less than 0.09.

IV. CONCLUSION

The results of testing experimental models have shown that under the action of a horizontal load, the PSPC together with the columns can be considered as a system with one degree of freedom in the first approximation or as a system with an infinite number of degrees of freedom.

Comparison of the frequency values obtained theoretically in accordance with the recommendations of building codes and regulations for systems with one degree of freedom with the results of experimental studies showed that these values practically coincide (respectively equal to 12.5 and 11.8 Hz.

The periods of horizontal natural oscillations of the PSPC were in the range of 0.03 - 0.147 s, and the logarithmic decrements of the oscillations did not exceed 0.04. From the evenly distributed load over the entire coating, the struts in the support zone of the structure were the most loaded. The increase in the forces in the core elements of the structure, taking into account the vertical seismic load, amounted to a maximum of 18% for the model with a plan size of 3.0 x 3.0 m, and 14% for the 3.6 x 3.6 m model. The elements of the experimental models at all stages of loading worked in the elastic stage.

The nature of the deflections of the model corresponded to its tense state. The greatest deflection under normal symmetrical load was fixed in the middle of the model and is equal to 5.23 mm, which was 1/425 of the span and indicated sufficient rigidity of the model structure.

A comparison of the experimental data obtained with the results of calculations using the displacement method using finite elements showed their fairly good correspondence. The experimental data exceeded the calculated ones by only 12-19%. The tests have shown that the structure has sufficient strength, stability, rigidity and earthquake resistance. Based on the results obtained, recommendations are made for their use in the calculation and design of PSPCS for seismic areas [17].

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