UDC 534.1, 621.81-192

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EFFECT OF MUTUALLY AMPLIFYING ACTION OF TWO COORDINATE SHOCK LOADING IN PROBLEMS OF DYNAMICS OF KNOTS OF MACHINES

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ЕФЕКТ ВЗАЄМОПІДСИЛЮЮЧОЇ ДІЇ ДВОКООРДИНАТНОГО УДАРНОГО НАВАНТАЖЕННЯ В ЗАДАЧАХ ДИНАМІКИ ВУЗЛІВ МАШИН

Purpose. To define and analyze patterns of influence on the qualitative and quantitative parameters of mutually reinforcing action of two components of the kinematic coordinate shock loading on the vibration amplitude of the object at the control points on the basis of two-parameter amplitude-down hole-time characteristics.

Methodology. The study is based on fundamental approaches of applied mechanics, theory of modeling and vibration reliability. The pre-set parameters include inertial, dissipative and elastic characteristics of the test object, coordinates of its reference points while varied parameters are time parameters of two-dimensional external mechanical shock action, design factors of a supporting structure as well of the object itself and its pre-set reference points.

Findings. Factors of influence of the parameters of the two coordinate impact while testing the facilities of the spatial structure for vibration reliability are introduced, dependence of the quantities and gradient signs of changes in these factors on the design parameters of the supporting structure of the test object and geometric coordinates of the reference point on the object and the supporting structure (e.g., a platform of a many coordinate shaker).

Originality. For the first time, quantitative and qualitative patterns of influence factors dependence on the parameters of the two coordinate external mechanical loading, the test object and the support structure are defined for objects of the spatial structure based on two-parameter amplitude-downhole-time characteristics. As a measure of mutually increasing action of parameters of two-coordinate shock loading, it is suggested to use the influence coefficients described through amplitudes, duration and inter-coordinate temporal delay of shock influences.

Practical value. The examined shock influences in practice result in the refuses of the real objects of mining machinery manufacturing, aviation, transport and space machinery regarding stability of functioning and durability. For the particular assembly machines, the results are used when determining the regulatory regime of bench tests for multicoordinate impact force, which improves durability and reliability in operation.

Keywords: *two-coordinate shock loading, vibration reliability, dynamics of knots of machines*

Introduction. Constructions of modern machines, equipment and mechanisms of mining machinery, aviation, transport and space engineering are continuously developed and improved in the direction of increasing the power, rapidity and accuracy [1–5]. While seeking to reduce metal consumption and the size of metal, this leads to high dynamic loading, as well as to an increasing role of the vibrational movement of the machine knots [6]. Most of the units and components of such equipment make a set of nodes, blocks, and units installed on the supporting structure (housing) and belongs to a class of objects of the spatial structure (OSS), whose mechanical scheme is a system of spatially oriented inertial, elastic and dissipative elements.

Analysis of the recent research. Theoretical issues related to the peculiarities of manifestation of the synergistic action effects in the task to test the spatial structure objects for vibration reliability problems are solved in the works [6–8]. It was found that this excludes the underestimations of indicators of the vibratory activity of objects, diagnosed by at bench tests and, consequently, their unexpected failures at vibration reliability in use. Mutually reinforcing action of parameters of the deterministic multi-axis vibration was analyzed on the basis of amplitude – phase – frequency characteristics, and the effectiveness of OSS bench tests on the multi-axis forward angular vibrating tables was showed.

The objective of the article is to define influence patterns for the of qualitative and quantitative parameters of mutually reinforcing actions of constituting

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two-coordinate kinematic mechanical shock loading on the vibration amplitude of the object at the control points, formalized on the basis of two-parameter amplitude-down hole-time characteristics.

Presentation of the main research. The present work is devoted to the numerical analysis of the mutually reinforcing action of the parameters of two-coordinate shock loading, formalized by means of two-parameter amplitude-downhole-time characteristics (ADTC) of the OSS through mechanical and geometric parameters of the supporting structure (housing products), as well as the object itself and its defined control points.

Fundamental equation of OSS vibrations in the time domain, produced in the control room and then in the normal forms, were the basis of research. This functional dependence of the vibration parameters of the object on the parameters of the external kinematic effects is analyzed based on the extremality properties [6, 7].

As a measure of the mutually reinforcing action of the parameters of the two-coordinate shock loading on the dynamic state of the OSS the coefficients of influence are accepted

$$Ks_y = \frac{\max Y - \max Y^*}{\max Y^*} \cdot 100\%;$$
$$Ks_z = \frac{\max Z - \max Z^*}{\max Z^*} \cdot 100\%;$$
$$Ks_\theta = \frac{\max \theta - \max \theta^*}{\max \theta^*} \cdot 100\%; \qquad (1)$$
$$Ks_r = \frac{\max r - \max r^*}{\max r^*} \cdot 100\%.$$

Where max Y, max Z, max θ, max r are the maximum values of functions

$$\max_t |y(t,T,\tau)| = f_1(T,\tau); \quad \max_t |z(t,T,\tau)| = f_2(T,\tau);$$
$$\max_t |\theta(t,T,\tau)| = f_3(T,\tau); \quad \max_t |r_{K1,2}(t,T,\tau)| = f_4(T,\tau),$$

where r is the radius-vector of deviations of the control points of the test object from their positions in a state of static equilibrium of the object; τ, T is the duration and the XY time delay of shock impacts (the time interval between the leading edges of the rectangular shock pulse in the direction of the vertical and horizontal coordinates). Here, the quantities max Y^*, max Z^*, max θ^*, max r^* are determined by the expression max ($y = f_1(5, 1)$), max ($z = f_2(5, 1)$), max ($\theta = f_3(5, 1)$), max ($r = f_4(5, 1)$). In this case the maximum values for the submodular function in the version accepted as the parameters max X^* ($X = y, z, \theta, r$) when the OSS has time to come to a state of static equilibrium before the arrival of subsequent shock impacts. For the mechanical object analyzed in the experiment it was found that this occurs at magnitudes $\tau = 1s$ and $T = 5s$. The influence coefficients $Ks_i(T, \tau)$ ($i = y, z, \theta, r$) are zero at the action of indicated perturbations.

On the base of the two-dimensional ADTC ($f_k(T, \tau)$ ($k = 1–4$)), the work defines and analyzes quantitative and qualitative characteristics of the behavior of the influence coefficients (1) when changing the τ, T parameters of the two-coordinate kinematic shock impact of a rectangular shape, as shown in Fig. 1 where A is the pulse amplitude.

The kinematic excitation at an object is formalized as

$$V_{Z_1}(t) = V_{Z_2}(t) = \begin{cases} A, t \in [0,\tau] \\ 0, t \in (\tau, +\infty) \end{cases};$$
$$V_{y_1}(t) = V_{y_2}(t) = \begin{cases} 0, t \in (0,T) \cup (T+\tau, +\infty) \\ A, t \in [T, T+\tau] \end{cases}. \qquad (2)$$

The advantage of the considered two-dimensional ADTC over the uniform amplitude-boreholes and amplitude-time characteristics is their absolute informative value regarding the following basic characteristics of mechanical vibration systems [6, 7]: the number of the resonance peaks when $\tau = Var$ and $T = Var$; the values of the parameters of indicators of the mutually reinforcing action of the two-coordinate shock loading (coefficients of the influence $Ks_i(T,\tau)$). The mechanical scheme of the analyzed three-dimensional object under research is shown in Fig. 2. The following designations are adopted: *1–4* – structural elements, mod-

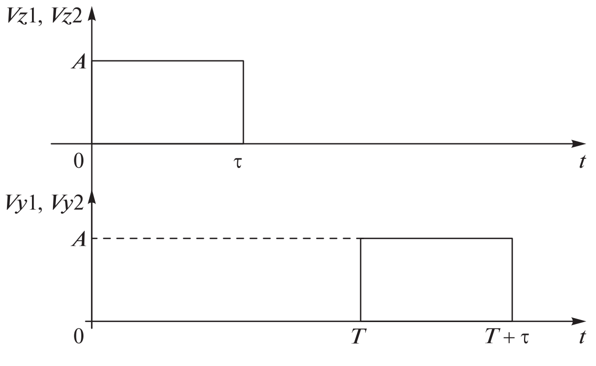

Fig. 1. Scheme of shock influence

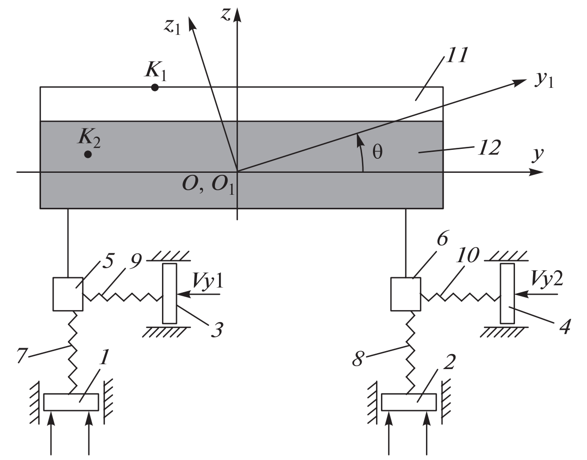

Fig. 2. Mechanical scheme of the object

eling supporting structure (body) of the item; *5, 6* – details of junction of the object with the product of housing; *7–10* – elastic-dissipative elements, modeling the generalized deformation characteristics of the suspension of the object in orthogonal directions; *11* – the basic constructive element of mass m_6, modeling the inertial properties of the object; *12* – the inertial additive element of mass m_a; V_{z1st}, V_{z2st} – vertical mounting displacement of constructive elements 1, 2, providing a static equilibrium of the object; Oyz, $O_1y_1z_1$ – fixed and movable system of coordinates accordingly, whose poles are the same in the position of static equilibrium. The feature of the object of research is a type of non-linear characteristics of the stiffness of elastic elements *7, 8* of its suspension bracket (Table Entry 8).

With the aim to facilitate the analysis and interpretation of results, as well as to make the results of studies of generalizing practical importance, the work represents the object as a set of basic inertial member 11 and the inertial additive element 12, which is embedded in the base, informing OSS the properties of the parametric irregularity of the dynamic model. In a particular case, the circuit of the research object, shown in Fig. 2, simulates the mining machinery units, seismic protection, aviation, space technology, as well as the crews of the rail and road transport. For example, with regard to mining and transport equipment it occurs when with machine working and the object moving along the route, the download changes; as for the aviation technology, the mounted unit is forcibly separated from the frame structure during the flight of the object. In this case, there obviously occurs a change of mass characteristics of the object, its moment of inertia, as well as the coordinates of the points fixing elastic-dissipative elements, etc., that is, the parameters of the dynamic model. In the paper, this object property is defined by the term "the parametric infrequency of the dynamic model".

As a result of the given shock impacts $Vz1$, $Vz2$, $Vy1$, $Vy2$ of constructive elements 1–4 of the supporting structure of the item, the research object executes three-dimensional vibrations in yOz plane. It has three degrees of freedom: the ability to move in the direction of the axis Oy and Oz, and rotate around the point O_1 (the center of mass). In practice, the considered shock impacts lead to the denials of the real objects regarding the stability of functioning and strength. Particularly when they appear periodically. As part of the task, the design scheme of the object reflects the main features of the real mechanical system, affecting the evaluation of its dynamic response, the features of connectedness of vibration; it is correct and structurally sufficient, taking into account the two-parameters of the analyzed influence coefficients and XY of the considered kinematic impact excitation.

In a time domain the dynamic model of the object with two-coordinate shock loading of kind (2) considering [6, 8] has the form

$$W \cdot Q_1 = Q_2,$$

where $Q_1 = [y, z, \theta]$ is a vector of linear and angular displacements of the object together with the mass center and around it; $Q_2 = [q_1, q_2, q_3]$ is a vector of input actions;

Table

Geometrical and mechanical parameters of the object

No.	OSS Parameters	The Object of the first type	The Object of the second type
1	The Mass m_6 of basic inertial element, kg	17000	
2	The Mass m_a of additive element, kg	0	8050
3	The Mass of generalized inertial element, kg	17 000	25 050
4	The coordinates of the center of basic element's masses, m	(0; 0.57)	(0; 0.64)
5	The moment of inertia of the generalized element, kg · m^2	250 692.67	251 589.33
6	The resistance ratios of elastic elements 7–10 of the suspension , N · s/m	$24 \cdot 10^3$	
7	The coefficients of the stiffness of elastic elements 9, 10 of the parallel axes, Oy, N/m	$0.475 \cdot 10^5$	
8	The coefficients of the stiffness of elastic elements 7, 8 of the parallel axes, Oz, (z – dimension in the formula is in meters), N/m	$5\cdot10^4\cdot\sqrt{6\cdot10^3\lvert z\rvert+1}$	
9	The Coordinates of the fixing points of elastic elements 7, 9 and 8, 10, m	(–3.2; –1.12); (3.2; –1.12)	(–3.2; –1.19); (3.2; –1.19)
10	The coordinates of the control points, m	K1 (–3.2; 2.0); K2 (–6.0; 0.5)	K1(–3.2; 1.93); K2(–6.0; 0.43)

$$q_1(t)=\left(b_y\cdot P+c_y\right)\cdot V_{y_1}(t);$$

$$q_2(t)=b_z\cdot P\cdot V_{Z_1}(t)+c_z V_{Z_1}(t);$$

$$q_3(t)=b1_z\cdot P\cdot y_{11}\cdot V_{Z_1}(t)+b2_z\cdot P\cdot y_{12}\cdot V_{Z_2}(t)+$$
$$+c1_z\cdot y_{11}\cdot V_{Z_1}(t)+c2_z\cdot y_{12}\cdot V_{Z_2}(t)-$$
$$-(b1_y\cdot P+c1_y)\cdot z_{12}\cdot V_{y_1}(t)-(b2_y\cdot P+c2_y)\cdot z_{13}\cdot V_{y_2}(t);$$

$W=\begin{pmatrix} W_y & 0 & -W_{y\theta} \\ 0 & W_z & W_{z\theta} \\ -W_{y\theta} & W_{z\theta} & W_\theta \end{pmatrix}$ is a matrix of transfer functions of the study object;

$$W_y=M\cdot P^2+b_y\cdot P+c_y;$$

$$W_z=M\cdot P^2+b_z\cdot P+c_z;$$

$$W_\theta=I_c\cdot P^2+\left(b1_y\cdot P+c1_y\right)\cdot z_{12}^2+\left(b2_y\cdot P+c2_y\right)\cdot z_{13}^2+$$
$$+(b1_z\cdot P+c1_z)y_{11}^2+(b2_z\cdot P+c2_z)y_{12}^2;$$

$$W_{y\theta}=\left(b_y\cdot P+c_y\right)\cdot z_{12};$$

$$W_{z\theta}=b1_z\cdot P\cdot y_{11}+b2_z\cdot P\cdot y_{12}+c1_z y_{11}+c2_z y_{12},$$

where $M = m_b + m_a$ is the mass of generalized inertial element; $P=\frac{d}{dt}$ is the operator of differentiation; $c_y = c1_y + c2_y$; $c_z = c1_z + c2_z$; $b_y = b1_y + b2_y$; $b_z = b1_z + b2_z$; $c1y$, $c2y$, $b1y$, $b2y$ are the coefficients of stiffness and elastic-dissipative resistance of elements 9, 10; $c1z$, $c2z$, $b1z$, $b2z$ are the coefficients of stiffness and elastic-dissipative resistance of elements 7, 8; I_c is the moment of inertia of the object relative to the axis passing through its center of mass; y_{11}, y_{12} are coordinates of the points fixing the elastic elements 7, 8 accordingly; $z_{12} = z_{13}$ are the coordinates of points of fastening of the elastic elements 9, 10; $Vz1 = Vz2$; $Vy1 = Vy2$.

The dynamic model of the object of research is presented in the normal Cauchy form and solved by the Runge-Kutta method of fourth-order accuracy.

As in the expressions (1) the values max Y^*, max Z^*, max θ^*, max r^* are constant values for a particular object, the behavior of the coefficients of influence is uniquely determined by the character of variation of the corresponding functions of two variables

$$\max_t\left|y(t,T,\tau)\right|=f_1(T,\tau);$$

$$\max_t\left|z(t,T,\tau)\right|=f_2(T,\tau);$$

$$\max_t\left|z(t,T,\tau)\right|=f_2(T,\tau);$$

$$\max_t\left|r_{K1,2}(t,T,\tau)\right|=f_4(T,\tau).$$

They are analyzed in the work for the geometrical and mechanical OSS parameters shown in Table.

Here, the objects of type 1 and 2 differ in masses of the additive element, respectively, with $m_a = 0$ and $m_a = 8050$ kg.

For example, Fig. 3–4 for the type 1 object shows the characteristics of the maximum deviations of coordinates of its center of mass and the reference point K_2 from its equilibrium position while varying τ and T in the range (0–5) c, where the positions *a*, *b*, *c* show the variations in coordinate direction *Y, Z,* θ, respectively.

The same characteristics for OSS of the second type are shown in Fig. 5–6.

As a result of the cumulative behavior analysis for ADTC $f_1(T,\tau)$, $f_2(T,\tau)$, $f_3(T,\tau)$, $f_4(T,\tau)$ we installed

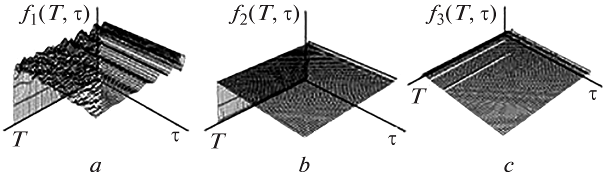

Fig. 3. Amplitude-downhole-time characteristics of the object:

a — deviations in the direction of Z coordinate; b — deviations in the direction of Y coordinate; c — deviations in the direction of θ *coordinate*

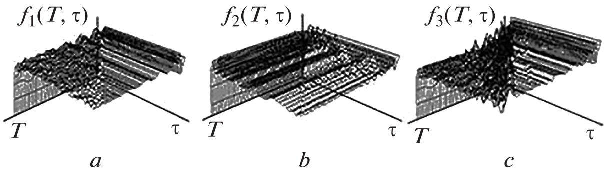

Fig. 4. Amplitude-downhole-time characteristics of the object:

a — deviations in the direction of Z coordinate; b — deviations in the direction of Y coordinate; c — deviations in the direction of θ *coordinate*

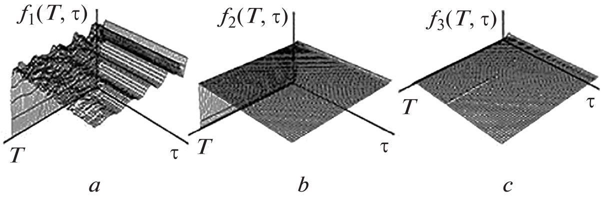

Fig. 5. Amplitude-downhole-time characteristics of the object:

a — deviations in the direction of Z coordinate; b — deviations in the direction of Y coordinate; c — deviations in the direction of θ *coordinate*

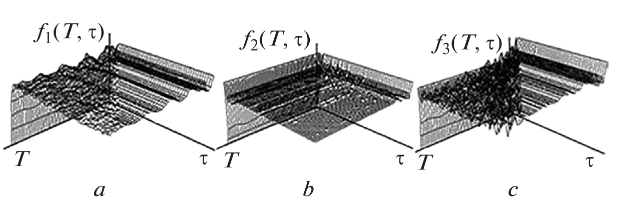

Fig. 6. Amplitude-downhole-time characteristics of the object:

a — deviations in the direction of Z coordinate; b — deviations in the direction of Y coordinate; c — deviations in the direction of θ *coordinate* the qualitative and quantitative dependences of coefficients influencing $Ks_i(T, \tau)$ ($i = y, z, \theta, r$) from the effect of parametric irregularities of the OSS dynamic model. For the test object analyzed in the work with changing mass of the inertia additive element in the range of $m_a = [0 \div 8050]$ kg, the ranges of change of influence coefficients adopted the following values: for the center of mass of the generalized inertial element $Ks_y = [21.9 \div 9.3]$ %, $Ks_z = [5.3 \div 3.7]$ %, $Ks_\theta = [20.1 \div 14.9]$ %; for the control point $K_1 - Ks_y = [38.4 \div 26.1]$ %, $Ks_z = [0.6 \div 6.2]$ %, $Ks_r = [47 \div 40.4]$ %; for the control point $K_2 - Ks_y = [23.9 \div 11.9]$ %, $Ks_z = [35.2 \div 25.4]$ %, $Ks_r = [58.8 \div 48.5]$ %.

At the same time there occurs dependence of the signs of gradients of changing influence coefficients on the position of the analyzed point in the internal volume of the object hull. For example, at a reference point K_1, for the vertical coordinate Z, as opposed to other considered points of the test object (point K_2, and the center of mass) the effect of the positive dynamics of change of influence coefficient Ksz appears, while an increase in mass inertia of the additive element in the range $m_a = [0 \div 8050]$ kg leads to its increase in 10.3 times. Moreover, we installed quantitative and qualitative dependence of the time parameters τ, T of the two-coordinate shock loading of kinematic excitation of the object, with which the conditions of $Ks_i(T, \tau) = \max(i = y, z, \theta, r)$ are achieved, on the geometric coordinates of the analyzed point in the $O_1y_1z_1$ system. For example, at $m_a = 0$, the following quantities of durations τ and the time lag T of shock loadings are obtained: for the center of mass in the coordinate $y - \tau = 1.1$ s, $T = 0.6$ s, in the coordinate $z - \tau = 0.3$ s, $T = 1.3$ s, in the coordinate $\theta - \tau = 0.9$ s, $T = 1.3$ s; for the control point K_1: for the coordinate $y - \tau = 0.9$ s, $T = 0.9$ s, for the coordinate $z - \tau = 0.6$ s, $T = 0.1$ s, for the radius-vector of the point $- \tau = 0.9$ s, $T = 0.4$ s; for the control point K_2: for the coordinate $y - \tau = 0.9$ s, $T = 0.4$ s, for the coordinate $z - \tau = 0.9$ s, $T = 1.3$ s, for the radius-vector of the point$- \tau = 1.9$ s, $T = 1.6$ s. Thus, for example, for the radius-vector of the control point K_2 the condition $Ksr = \max$ is reached at values of the duration quantities τ and the time lag T, exceeding the similar for the control point K_1, respectively by 2.1 and 4.0 times.

Conclusion. The importance of the studies carried out in the work, involves specifying the features of occurrence of effect of mutually reinforcing action of multi-coordinate mechanical shock loading from the supporting structure as applied to problems of the vibration reliability of the spatial structure of objects; the features are determined by coefficients influence. The obtained results should be considered when determining the normative operational mode of the object. Disregard of the established effect leads to a reduction of durability and reliability of an object in operation.

It should also be noted that with bench test for vibration reliability, the considered option of vibrations of the product hull is implemented by the platform of two-coordinate shock vibrating bench, whose development and implementation relates to the topical problems of modern testing equipment.

The practical significance of the obtained results is shown while solving the problems of vibration resistance, vibration strength and vibration diagnostics of knots and units of machines relating to the objects of the spatial structure, designed for operation under conditions of multi-coordinate impact action, as well as in the synthesis of constructive schemes.

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Вплив динамічних процесів у шахтних підйомних установках на безпеку експлуатації стволів з порушеною геометрією / С.Р. Ільїн, В.І. Самуся, І.С. Ільїна, С.С. Ільїна // *Науковий вісник Національного гірничого університету*. – 2016. – № 3. – С. 42–47.

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Мета. Встановити та проаналізувати закономірності впливу на якісні й кількісні параметри дії складових двокоординатного кінематичного ударного механічного навантаження, що взаємопідсилюється, на амплітуди коливань об'єкта в контрольних точках, формалізовані на базі двопараметричних амплітудно-шпаруватисно-часових характеристик.

Методика. Дослідження базуються на фундаментальних підходах прикладної механіки, теорії моделювання та вібронадійності. Заданими параметрами є інерційні, дисипативні й пружні характеристики об'єкта випробувань, координати його контрольних точок, варійованими – тимчасові параметри двомірної зовнішньої механічної ударної дії, конструктивні параметри несучої конструкції, а також самого об'єкта та його заданих контрольних точок.

Результати. Уведені коефіцієнти впливу параметрів двокоординатної ударної дії при випробуваннях об'єктів просторової структури на вібронадійність, встановлена залежність величин і знаків градієнтів зміни вказаних коефіцієнтів від конструктивних параметрів несучої конструкції, об'єкта випробувань і геометричних координат контрольної точки на об'єкті й несучій конструкції (наприклад, платформі багатокоординатного вібростенда).

Наукова новизна. Уперше для об'єктів просторової структури на базі двопараметричних амплітудно-шпаруватисно-часових характеристик встановлені якісна й кількісна закономірності коефіцієнтів впливу від параметрів зовнішнього двокоординатного механічного навантаження, об'єкта випробувань і несучої конструкції. В якості міри взаємопідсилюючої дії параметрів двокоординатного ударного навантаження запропоновано використовувати коефіцієнти впливу, що формалізовані через амплітуди, тривалість і міжкоординатне часове запізнювання ударних впливів.

Практична значимість. Ударні впливи, що розглядаються, призводять на практиці до відмов реальних об'єктів гірничого машинобудування, авіаційної, транспортної та космічної техніки за стійкістю функціонування й міцністю. Для конкретних вузлів машин отримані результати використовуються при визначенні нормативного режиму стендових випробувань на багатокоординатну ударну дію, що забезпечує підвищення довговічності та надійності об'єкта в експлуатації.

Ключові слова: *двокоординатне ударне навантаження, вібронадійність, динаміка вузлів машин*

Цель. Установить и проанализировать закономерности влияния на качественные и количественные параметры взаимоусиливающегося действия составляющих двухкоординатного кинематического ударного механического нагружения на амплитуды колебаний объекта в контрольных точках, формализованные на базе двухпараметрических амплитудно-скважностно-временных характеристик.

Методика. Исследования базируются на фундаментальных подходах прикладной механики, теории моделирования и вибронадежности. Заданными параметрами являются инерционные, диссипативные и упругие характеристики объекта испытаний, координаты его контрольных точек, а варьируемыми – временные параметры двухмерного внешнего механического ударного воздействия, конструктивные параметры несущей конструкции, а также самого объекта и его заданных контрольных точек.

Результаты. Введены коэффициенты влияния параметров двухкоординатного ударного воздействия при испытаниях объектов пространственной структуры на вибронадежность, установлена зависимость величин и знаков градиентов изменения указанных коэффициентов от конструктивных параметров несущей конструкции, объекта испытаний и геометрических координат контрольной точки на объекте и несущей конструкции (например, платформе многокоординатного вибростенда).

Научная новизна. Впервые для объектов пространственной структуры на базе двухпараметрических амплитудно-скважностно-временных характеристик установлены качественная и количественная закономерности зависимости коэффициентов влияния от параметров внешнего двухкоординатного механического нагружения, объекта испытаний и несущей конструкции. В качестве меры взаимоусиливающегося действия параметров двухкоординатного ударного нагружения предложено использовать коэффициенты влияния, формализованные через амплитуды, длительность и межкоординатное временное запаздывание ударных воздействий.

Практическая значимость. Рассматриваемые ударные воздействия на практике приводят к отказам реальных объектов горного машиностроения, авиационной, транспортной и космической техники по устойчивости функционирования и прочности. Для конкретных узлов машин полученные результаты используются при определении нормативного режима стендовых механических испытаний на многокоординатное ударное воздействие, что повышает долговечность и надежность объекта в эксплуатации.

Ключевые слова: *двухкоординатное ударное нагружение, вибронадежность, динамика узлов машин*

Рекомендовано до публікації докт. техн. наук Д. Л. Колосовим. Дата надходження рукопису 12.11.15.