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Nonlinear vibrations of a high-rise structure with a dynamic vibration damper

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Abstract. *Objective.* To study the dynamic behavior of high-rise structures with dynamic oscillation dampers under various kinematic influences, taking into account the nonlinear elastic, viscoelastic, and elastoplastic properties of the structure's material and the viscoelastic properties of the oscillation damper. Dynamic oscillation dampers can be used both at the stage of design, development and construction of structures, as well as in cases where structural quality deficiencies are identified during operation. Their adjustment allows for a simple way to achieve the desired effect of reducing oscillation levels. *Methods.* A mathematical model, methodology, and algorithm are proposed for evaluating the dynamic behavior of high-rise structures equipped with a dynamic vibration absorber, taking into account the nonlinear properties of materials under actual operating conditions. To account for internal dissipation in the structure's material, a nonlinear hereditary Boltzmann–Volterra viscoelasticity model is employed, along with elastic-plastic properties based on a bilinear diagram. This model is characterized by a hysteresis loop, which describes the relationship between the structure's response and deformation, represented in the form of a parallelogram. *Results.* The forced vibrations of high-rise structures near the resonance mode were investigated taking into account the linear, nonlinear elastic, viscoelastic and elastic-plastic properties of the structure material with a dynamic vibration damper under various kinematic effects in the base. The reliability of the method was verified by a test example considering the reaction of an elastic-plastic frame as a system with one degree of freedom under a given load. The effect of vibration damping of a high-rise structure was revealed taking into account the nonlinear viscoelastic and elastic-plastic properties of the structure material together with a viscoelastic dynamic vibration damper. *Conclusion.* The influence of the material's dissipative properties on the structure's oscillations has been established. Recommendations for optimizing the structure's performance, taking into account the dynamic oscillation damper, have been proposed. The effectiveness of damping oscillations in a high-rise structure has been demonstrated, considering the nonlinear viscoelastic and elastoplastic properties of the structure's material in conjunction with a viscoelastic dynamic oscillation damper.

Keywords: height structure, kinematic impact, nonlinear elastic, viscoelastic and elastic-plastic properties of the material, dynamic oscillation damper, finite element method, resonance mode.

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Introduction

The problem of reducing the vibration level of structures arises in various fields of engineering, industrial and civil engineering, heavy, transport, energy engineering, etc. In this case, first of all, it is necessary to meet the technological requirements imposed by the operating conditions, to protect structures and structures from the harmful effects of vibrations.

To date, various methods and means are known to combat unacceptable vibrations of structures, in particular, changing the rigidity and inertia parameters of the structure in order to detach from resonances; increasing damping properties by using materials and structures with high absorption capacity, for example, special coatings; the use of vibration isolation and various vibration dampers. Each of the mentioned methods has, of course, its own rational field of application. Dampers occupy a special place in this list due to the fact that their use can be provided not only at the design and construction stage, but also in the case when unsatisfactory dynamic qualities of the structure are identified already during its operation. The advantage of dampers is also that, with a relatively low cost of additional material, they make it relatively easy to achieve the desired effect of reducing the level of vibrations.

A dynamic vibration dampener (DHC) is a device in which an inertial force occurs, reducing the level of vibrations of the protected structure. Most often, DHA is performed in the form of an additional mass attached by means of elastic and damping elements to the protected structure. The mass of the damper is a solid body to which removable weights, an elastic structure and a container filled with individual loads, bulk materials, and liquid can be attached. Steel springs, rubber elements, elastic rods or plates are used as elastic elements. Materials with enhanced dissipative properties are used to dissipate energy.

The main research areas in the field of vibration damping are related to optimizing parameters and evaluating the effectiveness of DHCS in stationary and transient modes under various dynamic influences: investigating the effectiveness of complicated linear and nonlinear DHCS; determining the rational scope of DHCS for real structures that have fairly simple and very complex design schemes; developing effective methods for calculating structures with attached DHCS; methods for optimizing DHA parameters; creation of new DHA technological solutions with the required dynamic qualities.

The purpose of this work is to develop a methodology and algorithm for solving the problem of forced fluctuations of high-rise structures with inelastic properties of a material with DHC, to study the dynamics of specific structures using DHC, and to analyze the results obtained in terms of detecting effective operating conditions.

Numerous scientific papers have been devoted to the problem of calculating structures with DHC for stationary and non-stationary impacts, taking into account the occurrence of various types of deformations in the structure. Let us focus on those of them that are of direct interest in assessing the effective damping of vibrations of a structure using a DHC.

Such scientific papers include the following.

• In [1], a new vibration damping system is considered to reduce wind vibrations of steel chimneys and other thin structures. A damping system is proposed using standard hydraulic dampers fixed between the chimney and the roof of the power plant building on which it is located. An example is a steel chimney with a height of 125 m and a diameter of 4.6 m in Hanover (Germany). Using finite element analysis, a numerical simulation of a chimney with dampers in the form of beam elements was carried out and the damping coefficient of the system and the oscillation amplitudes were determined.

• The work [2] shows the effect of interference between two tall round chimneys located at different axial distances and angles of incidence. The aim of the work is to quantify the increase in wind load and the dynamic reactions of the structure in order to provide recommendations for the design of the distance between the chimneys and their orientation. In the study, a 200-meter concrete chimney of variable cross-section was modeled on a scale of 1:200, and interference coefficients for surface pressure were obtained as the ratio of loads between an isolated case and an arrangement with a second, adjacent pipe.

• [3] presents a numerical scheme for combining three models to evaluate the effectiveness of tuned liquid dampers in reducing wind vibrations of thin structures. The main advantages of the numerical scheme include: direct modeling of the nonlinear interaction of liquid and structure, effective virtual testing of several configurations of liquid dampers, applicability to various structures and wind phenomena.

• In [4], high reinforced concrete chimneys are investigated, which are thin structures that are sensitive to dynamic wind loads. Dampers with adjusted mass, installed in structures to reduce unwanted vibrations under dynamic loads, are considered. A dynamic analysis of the wind of two chimneys with a height of 200 and 220 m was performed using computational fluid dynamics in ANSYS. The study showed that properly designed systems of multiple dampers with an optimal weight ratio can effectively reduce wind-induced vibrations of tall, thin chimneys by more than 20

• The work [5] provides an assessment of steel chimneys vulnerable to vortex vibrations and their control using aerodynamic vibration dampers. The vibration dampener design is located in the upper part of a cylindrical steel chimney with a height of 85 m. The study successfully demonstrated the possibility of determining wind load and quantifying the effectiveness of vortex control, which was made possible by testing a dynamic chimney damper in a wind tunnel.

• In [6], a solar chimney is considered based on an innovative concept aimed at obtaining renewable energy through the use of solar radiation. A high-rise reinforced concrete tower is located in the center of a large solar collector. Sunlight heats the air under the collector, and as a result of convection, the air rises through the tower. The air flow drives the wind turbines at the base of the tower, generating electricity. The tower damping coefficient is estimated and the expected wind load conditions, including turbulence and directional shear, are characterized.

• In [7], industrial chimneys are studied, which are subject to fluctuations caused by wind, both in the direction of the line and across the wind. Resonance can occur due to velocity fluctuations interacting with the dynamic properties of the chimney. Mathematical models and approaches for quantifying these wind effects are considered. An analysis of the aerodynamic coefficients and assumptions about the beam-shell ratio shows the effect on wind load profiles and stress distribution. The results indicate the need for a more precise definition of parameters such as damping and amplitude limits, taking into account the shape of the modes and the scale of turbulence.

• In [8], wind vibrations of a 75-meter chimney structure in Madagascar are analyzed using viscoelastic dampers. The simulation of the chimney structure by finite elements is performed with elements of a viscoelastic damper. Dynamic analysis shows that viscoelastic dampers effectively reduce wind-induced dynamic chimney reactions, especially displacement reactions, which are reduced by more than 36 pct. with optimized placement.

• In [9], the use of vibration dampers is considered to reduce vibrations caused by wind in chimneys. The amplitude of the resonant vibrations can be limited by using a damper system with adjusted mass, optimal mass, stiffness and damping. The chimney is modeled as a system with one degree of freedom. Examples of specific damping systems used in practice, such as a Tretner damper with an oil damper, are given.

• [10] examines the dynamic behavior and analysis of tall reinforced concrete chimneys. The 275 m high-rise chimney is modeled in STADD Pro using girder and plate elements. The analysis allowed us to determine the natural frequencies and modes of the chimney. The first two frequencies were 0.252 Hz and 1.055 Hz.

• In [11], the use of tuned mass dampers is considered to reduce the seismic reaction of a reinforced concrete chimney with a height of 265 m, which is subject to pulsed underground impacts close to destruction. Pulsed ground movements with velocity pulses are critical for tall, thin structures. Three damping schemes have been investigated - single, several dampers with equal rigidity, and several dampers with equal masses. The chimney was modeled as 30 Euler-Bernoulli beams with unit masses. The results showed that when the pulse period is close to the oscillation period of the chimney, a reduction in displacement by 10... 35

• In [12], high-rise reinforced concrete chimneys are investigated, which are subject to fluctuations caused by wind, which lead to structural damage. Mass-adjusted dampers are used to control these fluctuations. The dampers work due to the additional small mass attached to the structure by means of springs and dampers. A 180 m high chimney with various diameters and thicknesses is analyzed for wind and seismic loads. Dynamic analysis shows that the addition of a damper reduces offsets by 23 pct. compared to the original design. The study shows that dampers effectively reduce wind-induced fluctuations in high-rise chimneys.

• In [13], steel chimneys are considered as thin structures subject to fluctuations caused by wind. Vibration dampers are installed to suppress resonance. Dampers tuned to the natural frequency of the chimney consists of a small additional mass on the spring and pusher and limits vibrations. Wind vibrations of two thin pipes 60 m and 120 m high were studied. Adjusting the mass of the damper shifted the frequency away from resonance, and increasing the damping reduced the amplitude.

• [14] provides an overview of high-rise structures subject to a phenomenon known as vortex resonance. Resonance occurs when the vortices acting on the structure in frequency coincide with one of the natural frequencies of the structure, causing it to oscillate. If proper measures are not taken, this resonance can lead to fatigue and even catastrophic destruction. Various options for mitigating these problems have been considered. It is indicated that the methods of dynamic analysis and wind tunnel testing, computational fluid dynamics modeling and finite element modeling make it possible to understand the influence of wind and obtain tools for assessing and eliminating potential resonant conditions.

• In [15], the dynamic characteristics and updating of the model of a brick chimney of a high-rise building using vibration measurements are investigated. The frequencies of the first shapes, damping coefficients, and mode shapes were determined. The initial frequencies had an error of up to 24 pct. compared to the experiments, which indicates the excessive rigidity of the analytical model. Dynamic identification and updating of models made it possible to quantify the modal properties of the chimney and identify hidden damage.

• In [16], the use of dynamic dampers to reduce fluctuations in high-rise buildings is investigated. It describes the use of viscoelastic materials to create damping elements, as well as mathematical models used to calculate them. The simulation results showed that the use of dynamic dampers can significantly reduce the amplitude of building vibrations and increase its stability in conditions of strong external influences, such as earthquakes.

• In [17–19], studies of the dynamics of various axisymmetric structures are presented, taking into account the nonlinear elastic and viscoelastic properties of building materials. The natural frequencies, vibration decrements, and amplitude-frequency characteristics of the structures under consideration under stationary kinematic influences are determined, and some mechanical effects that occur when evaluating the dynamics of structures are identified.

• In [20], a newly developed vertical steel tubular damper is considered, which has great lateral rigidity and excellent ability to dissipate energy during earthquakes. The improved performance of the structure is checked analytically using a four-story steel moment frame equipped with steel tubular dampers. Dampers are placed between any two points where there is a large relative motion during an earthquake. Nonlinear dynamic analysis of the structure using PERFORM-3D software has shown significant benefits from equipping the structure with steel tubular dampers. Structures properly designed with dampers require only minimal post-earthquake inspection and limited damage.

• In [21], a modified tubular damper design is proposed, called an X-shaped tubular damper (HPD). The damper is made by connecting two oppositely arranged pipe halves, forming an X-shaped core, which is then bolted to the connecting plates. Cyclic tests were carried out on 5 bolted CPDs and 2 welded CPDs to study the patterns of strength development, hysteretic characteristics, energy dissipation and failure modes. Experimental results have shown that bolted CPDs can provide good plasticity and stable hysteresis ratios with both the standard cyclic protocol and the fatigue cyclic protocol. The connected pipe halves can successfully form elastic fastening modes and increase the induced secondary strength with large lateral movements. Welded CPDs had a weaker energy dispersing capacity due to early crack failures, but they can provide higher rigidity and elastic consistency.

• In [22], a new passive energy dissipative earthquake device called a two-tube damper (DTD) was studied. The device consists of two pipes welded in selected locations and operated by shear. Inelastic cyclic deformation dissipates energy mainly due to the bending of the pipe body. However, with large movements, a tension diagonal is formed in the middle of the device, which additionally adds rigidity and strength. The strength, rigidity, and energy dissipation of the DPD account for more than two previously studied single tubular dampers. Cyclic quasi-static tests were carried out on four samples of DPD. Good plasticity, energy absorption, and stable hysteresis loops were observed in all samples. A finite element model has been developed that takes into account non-linearity, large deformation, contact and damage to the material, for conducting parametric studies on various pipe sizes. The dependencies that determine the behavioral characteristics of the DPA are given for any pipe size.

• In [23], the characteristics of a tuned mass damper (NMD) installed in a pipe with a height of 183 m located on the edge of another pipe are investigated. Numerical and experimental results are given. For simulations, the wind effect is considered by solving several two-dimensional flow problems on a selected number of horizontal planes in the transverse direction to the stacks. On such planes, the Navier-Stokes equations are solved to evaluate the effect of liquid in various positions of chimneys and standard methods of interpolation in the vertical direction are used. An arbitrary Lagrange-Eulerian approach is used to consider a moving region, and a fractional-step scheme is used to solve the fluid field. For structural modeling, pipes are connected using three-dimensional end elements. The time integration procedure used for structural dynamics is based on the standard second-order Bossack method. For each time period, the fluid problem is solved, an aeroelastic analysis is performed, and the geometry of the fluid grid of each plane is updated in accordance with the movements of the structures.

• In [24], parametric research was used to estimate the value of the rotational components of the Earth's motion in seismic engineering. The first part of the paper is devoted to the derivation of a formula that can be used to express the importance of rotational components in comparison with classical seismic design without using them. Quasi-static analysis is used, assuming inertial forces. The form of the fundamental oscillation regime plays an important role. For reasons of simplicity, a well-known expression is used to estimate the first proper mode as an exponential function with different power coefficients that differ for different types of buildings. The possibility of changing the soil parameters is subsequently included in the formula for estimating the fundamental frequency of high-rise buildings. In the next part, general seismic analyses of complex FEM models of three-dimensional buildings and pipes are performed. The results of these analyses are then compared with the results of simplified calculations. Next, the importance of soil characteristics is discussed to determine whether rotational effects should be taken into account.

• In [25], the influence of the control parameters of a reactive vibration damper on the amplitude of seismic movements of a tower-type structure is investigated. The sensitivity of the response of an unsteadily moving tower to movement restrictions, to the velocity of the jet jet being ejected, and to the time of a single reactive impact is analyzed. An algorithm for determining optimal control parameters for reactive impacts is presented. An assessment of the effectiveness of using a reactive vibration dampener is given.

• The work [26] is devoted to the possibility of an experimental evaluation of the effectiveness of a mechanical vibration damper during the operation of an engineering structure. Modern mechanical vibration dampers, as a rule, do not allow to evaluate the effectiveness of their operation during operation. There is a risk of insufficient objectivity of the technical report issued by the manufacturer of the extinguisher. Using a specific example, a general overview of the possibility of evaluating the effectiveness of a mechanical vibration dampener in a high-rise structure within the framework of an independent scientific and technical expertise is presented.

• In [27], the problem of shifting the direction of collapse caused by the impact of a high-rise reinforced concrete chimney during explosive demolition is considered in combination with monitoring methods such as high-speed photography, piezoelectric ceramic sensor and explosion vibration monitor, using the example of a 180 m high-rise chimney. The results show that the pipe will experience multiple effects of weight loss and overweight during the settling process, causing waves of compressive stress in the pipe. With a large subsidence displacement, broken reinforced concrete at the bottom can have a significant buffering effect, and the preponderance effect gradually weakens until subsidence stops. The waveform of the monitoring point of the piezoelectric ceramic sensor is divided into three stages, which specifically characterize the process of explosive load development and pipe impact. The vibrations induced by the explosion are mainly high-frequency vibrations above 50 Hz; the vibrations induced by the collapse of chimneys are mainly low-frequency vibrations below 10 Hz. In the process of explosive destruction and collapse of a high-rise reinforced concrete chimney, due to the impact of subsidence, the wall of the support pipe is subjected to uneven force, which leads to a deviation in the direction of collapse.

• In [28], equivalent static wind loads (VSWR) are investigated, which are taken into account in structural design to account for peak dynamic wind effects. In practice, VSWRS are designed for structures without control. For flexible structures with vibration control devices, an ESR study is required. Inert vibration dampers (IVPs), due to their light weight and high performance, have recently attracted a lot of attention from researchers. The paper establishes the general analytical structure of the VSWR for structures with an IVP. Analytical optimal design formulas for IVPs with various configurations and installation locations are given. The evaluation of the VSWR for a high-rise chimney controlled by an IVP is illustrated, and the results showed a significant effect of reducing the VSWR of the IVP, especially for transverse vortex resonance. The presented approach can be applied to more complex structures and vibration control devices.

• In [29], an analysis of nonlinear oscillations of a complex dynamic system consisting of a hinge, a rod and a ball held together in a single way is given. A differential equation of motion of a pendulum is obtained taking into account the friction in the hinge and taking into account the resistance of the continuum. The solution of the problem is based on the law of conservation of energy, taking into account the dissipation of energy both in the hinge and during the movement of the bonded rod and ball in a viscous medium. It is analytically shown that the dynamics of the system under consideration is significantly affected by energy losses in the hinge, leading to a strong decrease in attenuation time during oscillatory motion, which is nonlinear. The numerical solution of the nonlinear equation indicates strongly inhomogeneous oscillations of the generalized coordinate, which was chosen as the angle of deviation of the pendulum from the vertical axis. The paper proposes a method for deriving differential equations of motion for complex dynamical systems.

• In [30], the problem of reducing the vibration level on the paws of electric machines using dynamic vibration dampers is considered. For this purpose, the paw of electric machines is represented as a sub-deformed solid with six degrees of freedom mounted on viscoelastic supports. An algorithm and a set of programs have been developed to study the dynamic characteristics of mechanical systems with a finite number of degrees of freedom. A real electric car has been replaced by a model of a rigid body with shock absorbers having six degrees of freedom. The equations of small vibrations of a solid body with dampers are derived using the Dalembert principle. A simplified system of equations is obtained that takes into account only three degrees of freedom. It was found that the optimal setting of the dampers is within the frequency range of 50.6...50.7 Hz and a two-mass damper at 10...15

• In [31], an effective numerical method is proposed for solving the inverse nonlinear problem of the movement of a compressor rotor disk in a thrust sliding bearing. A mathematical model of hydrodynamic and thermal processes in a bearing is constructed under the condition of axial movement of the rotor disk. The inverse nonlinear problem of determining the position of the rotor at a given change in the external load is formulated within the framework of the model. An iterative solution method using the solution of a direct problem is proposed. Numerical experiments have been conducted to demonstrate the effectiveness of the proposed approaches. A set of programs has been built that allows calculating a nonlinear system of rotor motion for various physical and geometric parameters.

As the above analysis of published scientific papers shows, each of these papers has both its advantages and some disadvantages, despite this, they are all used in solving specific practical problems.

Based on this analysis, it can be noted that the development of mathematical models, solution methods and the study of the dynamics of a high-rise structure using a dynamic vibration dampener is currently a very urgent and modern problem that needs to be solved.

1. Methodology

1.1. A mathematical model. In this paper, we consider the forced oscillations of the "DHC facility"system. The structure is considered as a cantilever beam of variable cross-section with a variable slope (Fig. 1) forming dampers with dampers installed at several points. The material of the structure is considered to be non-linearly elastic, viscoelastic and elastoplastic.

The elastic-plastic properties of the material are described by a bilinear diagram in which the hysteresis loop, characterizing the dependence of the reaction of the structure on deformation, is represented as a parallelogram (Fig. reffig:sx2).

This dependence is often bilinear and is characterized by three parameters (see Fig. 2): F, $tg\theta_1$, $tg\theta_2$.

When the material of the structure and the DHC springs are assumed to be linearly viscoelastic,

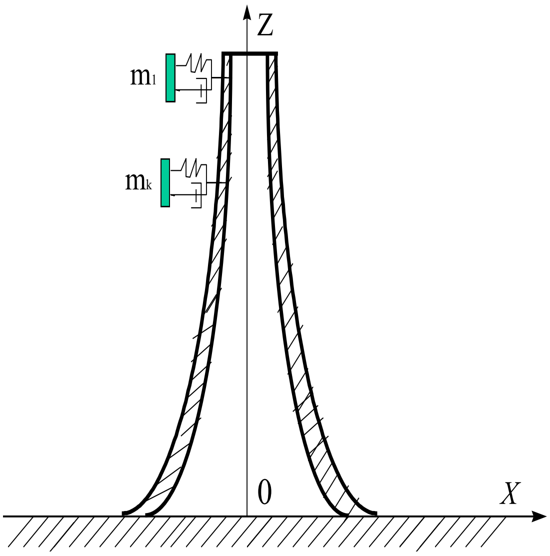

Fig. 1. Calculation scheme of a structure with DVD

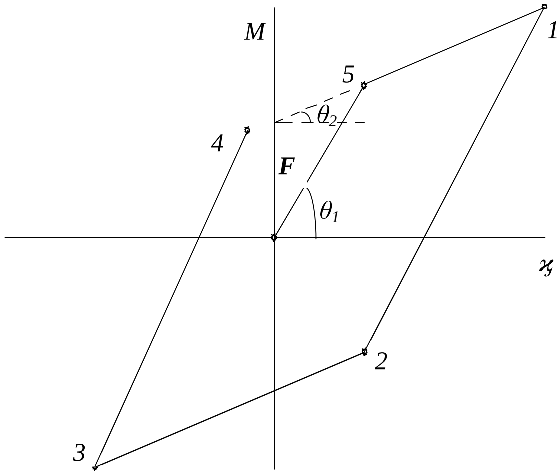

Fig. 2. Bi-linear deformation diagram

their properties are described by the hereditary Boltzmann-Volterra theory [33], that is

$$\tilde{\sigma}_z = E\left\{\varepsilon_z - \int_0^t R_1(t-\tau)\varepsilon_z(\tau)d\tau\right\},$$
$$\tilde{K}_{ki} = K_{ki}\left[w(t) - \int_0^t R_2(t-\tau)W(\tau)d\tau\right]. \tag{1}$$

Assuming the integral terms are small [34], the long modulus of elasticity of the material and the stiffness of the spring are reduced to complex relations of the form

$$\tilde{E} \approx E\left[1 - i\Gamma_1^s(p) - \Gamma_1^c(p)\right],$$
$$\tilde{K}_{ki} \approx K_{ki}\left[1 - i\Gamma_2^s(p) - \Gamma_2^c(p)\right]. \tag{2}$$

Здесь $\Gamma_1^c(p) = \int_0^\infty R_1(p)\cos p\tau d\tau$; $\Gamma_1^s(p) = \int_0^\infty R_1(p)\sin p\tau d\tau$; $\Gamma_2^c(p) = \int_0^\infty R_2(p)\cos p\tau d\tau$; $\Gamma_2^s(p) = \int_0^\infty R_2(p)\sin p\tau d\tau$ — cosine and sine Fourier images of the core; E — instantaneous modulus of elasticity of the structure material; K_{ij} — coefficient of instantaneous stiffness of the corresponding damper spring; p — frequency of external action; $(k, i = 1, 2, 3, \ldots)$.

It is necessary to determine the oscillation amplitudes at various points of the "structure with DHC"system at different frequencies of external influence, and it is necessary to establish the optimal parameters of the damper, which achieve the greatest effect of damping the amplitude of vibrations of the structure.

For the mathematical formulation of this problem, the Lagrange variational equation is used, based on the principle of Dalembert [33], that is

$$\int_0^l \tilde{M}_z\delta\left(\frac{\partial^2 w}{\partial z^2}\right)dz + \rho\int_0^l F(z)\frac{\partial^2 w}{\partial t^2}\delta w dz + \sum_{k=1}^N m_k\ddot{w}_k\delta w_k + \sum_{k=1}^N \tilde{K}_{k1}w_k\delta w_k = 0, \tag{3}$$

kinematic conditions

$$z = 0 : w = w_0(t); \qquad \frac{\partial w}{\partial z} = 0 \tag{4}$$

and the initial conditions

$$t = 0 : w(z,0) = 0; \qquad \frac{\partial w(z,0)}{\partial t} = 0. \tag{5}$$

Here ρ — the density of the structure's material; l — the length of the structure; $w(z,t)$ — the deflection of the structure; $\tilde{M}_z = \int_F x\tilde{\sigma}_z dF(z,t)$ — bending moment; $\varepsilon_z = -z\frac{\partial^2 w}{\partial z^2}$ — deformation of structures; $R_1(t)$, $R_2(t)$ — relaxation nuclei; $F(z)$ — cross-sectional area; m_k — attached quencher masses; N— number of attached masses; $\tilde{E}$, $\tilde{K}_{ki}$ — long-term modulus of elasticity and stiffness of the damper elements.

When solving the variational problem (3)–(5) under various kinematic influences, taking into account the elastoplastic, nonlinear viscoelastic properties of the structure material and the viscoelastic parameters of the DHC, the finite element method (FEM) [32] was used. A one-dimensional finite element with 4 degrees of freedom is chosen as the final elements.

Taking into account the elastic-plastic properties of the material, it was assumed that plastic hinges are formed in the end sections of the elements when the bending moments in these sections reach the yield point. When the direction of deformation was changed, the stiffness was restored to its initial value. Thus, a bilinear elastoplastic was used for the element (see Fig. 2) dependence "moment-curvature". The stiffness matrix of the model as a whole was compiled for each time interval by combining the stiffness of the elements, and for each element the stiffness was determined by a bilinear relationship in accordance with the achieved deformed state.

1.2. Algorithm of elastoplastic calculation. After using the FEM procedure [32, 35], the variational problem under consideration (3)–(5) is reduced to a system of ordinary differential equations of the form

$$[M]\{\ddot{w}\} + [C]\{\dot{w}\} + \{R(w(t))\} = -[M]\{\ddot{w}_0\}, \tag{6}$$

where $[M]$, $[C]$ are matrices of mass and dissipative forces of the structure; $\{R(w(t))\}$ — the restoring force determined by the hysteresis loop is selected depending on the deformed state achieved at the previous stage.

Next, the resulting system of nonlinear inhomogeneous differential equations (6) is solved by the Newmark method [32].

When solving a system of equations (6), the vector $\{R(w(t))\}$ is determined on each section of the loop using the universal formula

$$\{R\} = [K]\{w\} + \{P\} \tag{7}$$

with specific $[K]$ and $\{P\}$ corresponding to different stages of the oscillatory process.

The stiffness coefficient corresponding to the jth nodal point of the hysteresis loop and the corresponding ith component of the vector $\{P\}$ of the structure at the nth stage of the oscillatory process are calculated using the formulas

$$E_j(n) = 0.5\left\{[1 + (-1)^n]K_1 + [1 - (-1)^n]K_2\right\},$$
$$P_j(n) = (K_1 - K_2)\left(\sum_{i=-1}^{n-1}(-1)^i w_j^i\right), \tag{8}$$

where n is the number of the linear section on the hysteresis loop. In this case, the initial elastic region corresponds to the value of $n = 0$.

The coefficients are determined as follows: $K_1 = tg\theta_1$; $K_2 = tg\theta_2$; w_j^i — the values of w_j corresponding to the nodal points of the hysteresis loop, it is assumed that $w_j^{-1} = 0$.

1.3. A test case. The reliability of the technique was tested on a test example given in [32], where the reaction of an elastoplastic frame as a system with one degree of freedom under a given load was determined.

Calculations were performed for a system with a mass of $m = 0.1$, stiffness at the initial moment of $K_1 = 5$ and $K_2 = 0$ in the plastic stage. The attenuation coefficient is assumed to be $C = 0.2$. The integration step is $\Delta t = 0.1$s. The load $P(t)$ was set tabularly (Table).

As can be seen from the presented results (Table), the obtained movements are close to the data of [32], which indicates the reliability of the developed algorithm. Some difference in the results of the last five lines arose as a result of an insufficiently small integration step, which did not allow us to obtain more accurate values for the transition points on the hysteresis loop, which form the solution at subsequent integration steps.

Table. Results of calculations and their comparison with test data

t, c	$P(t)$	movement w		speed $\dot{w}$	
		given in [32]	received by the authors	are given in [32]	were obtained by authors
0	0	0	0	0	0
0.1	5	0.070	0.0704	2.11	2.113
0.2	8	0.493	0.4935	6.35	6.355
0.3	7	1.256	12563	8.03	8.041
0.4	5	2.000	2.002	6.58	6.579
0.5	3	2.519	2.520	3.57	3.565
0.6	2	2.687	2.687	−0.28	−0.265
0.7	1	2.475	2.476	−3.83	−3.828
0.8	0	2.010	1.967	−5.21	−6.016
0.9	0	1.456	1.356	−5.00	−5.715
1.0	0	1.042	0.903	−3.00	−3.05
1.1	0	–	0.774	–	0.453
1.2	0	–	0.968	–	3.173

2. Results

Using the algorithm described above, the fluctuations of a high-rise structure equipped with a DHC are investigated (Fig. 1). As an example of calculation, the dynamic behavior of the chimney of the Novo-Angrenskaya TPP (height $H = 330$ m, diameter at the lower base $D = 38$ m and at the upper level $D = 16.7$ m) was studied under various kinematic influences and with different laws of material deformation.

The calculations use a kinematic effect in the form of

$$z = 0: \ w_0 = \cos pt. \tag{9}$$

When studying the resonant oscillatory mode, it is necessary to set the kinematic effect with a frequency p close to the fundamental frequency ω of the system's vibrations. Here, $p \approx \omega$ is selected, where ω is the main natural oscillation frequency of the system, which coincides with the frequency of the impact of p.

2.1. Fluctuations of a high-rise structure with a DHC, taking into account the viscoelastic properties of the material and the damper. In this case, the construction material is assumed to be linear-viscoelastic. To describe the viscoelastic properties of the building material, the core of A.R. Rzhanitsyn $R(t) = \lambda \exp(-\beta t) t^{(\alpha-1)}$ was used, where $A = 0.0234$, $\alpha = 0.075$, $\beta = 0.00000014$, defined by from experimental creep curves of reinforced concrete [33].

At an impact frequency close to the natural oscillation frequency of the "DHC facility"system, the viscoelastic parameters of the damper spring were assumed to be $\Gamma_2^{\tilde{n}} = 0.2$, $\Gamma_2^{s} = 0.02$.

When using (2), the problem is simplified, and the system of differential equations (6) is reduced to a linear system of differential equations with complex coefficients, which is then solved by the Newmark method.

In Fig. 3 shows the changes in the horizontal displacements of w for the construction point ($z = 325$ m) (see Fig. 1) over time, taking into account the viscoelastic properties of the material and the viscous properties of the damper spring in the resonant oscillation mode — when exposed to the law at the base of the structure (9).

In Fig. 3 shows the results obtained without taking into account the damper (solid line) and taking into account the viscoelastic DHA (line with an asterisk).

A comparison of these results shows that a DHC tuned to the fundamental frequency of the "building with DHC"system almost completely eliminates large oscillation amplitudes in the resonant

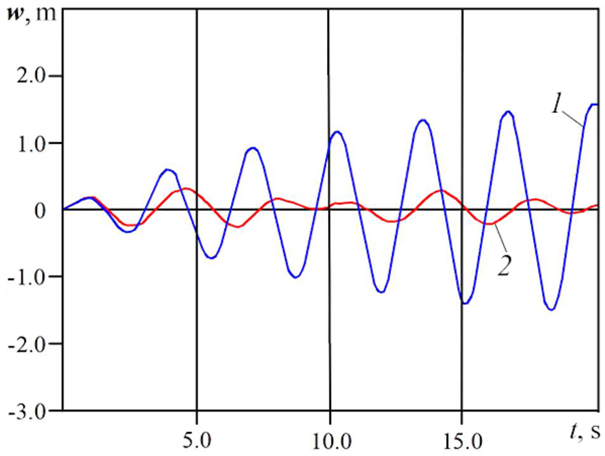

Fig. 3. Changes in horizontal displacements w of a point ($z = 325$ m) on the structure, considering the linear viscoelastic properties of the structure's material, without a damper (1) and with a DVD (2) under kinematic excitation (9)

mode. At the same time, the damper oscillates with a large amplitude, and the structure oscillates with a much smaller amplitude compared to without a damper.

2.2. Fluctuations of a high-rise structure with a DHC, taking into account the physically nonlinear deformation of the structure's material. The fluctuations of the "building with DHC"system are considered (see Fig. 1), taking into account the nonlinear viscoelastic properties of the structure's material in the resonant oscillation mode under the action of kinematic action at the base of the structure (9).

In this case, the material of the structure is considered both elastic and nonlinear-viscoelastic, and cubic nonlinearity [33] is used to describe the relationship between stress and deformation, that is

$$\widetilde{\sigma}_z = E\left\{\left[\varepsilon_z(t) - \int_0^t R(t-\tau)\varepsilon_z(\tau)d(\tau)\right] - \gamma\left[\varepsilon_z^3(t) - \int_0^t R_3(t-\tau)\varepsilon_z^3(\tau)d(\tau)\right]\right\}, \tag{10}$$

where E is the instantaneous modulus of elasticity of the material; $\boldsymbol{R}$, $\boldsymbol{R_3}$ — relaxation nuclei; $\boldsymbol{\gamma} =$ const > 0 — coefficient of nonlinearity.

In specific calculations, the nonlinearity coefficient γ was assumed to be $\gamma = 120,000$, which made it possible to describe the experimental curves $\sigma = f(\varepsilon)$ with the necessary accuracy for small deformations.

In this case, the frequency of exposure to p is assumed to be almost equal to the natural frequency of the ω system. The viscoelastic parameters of the damper spring are accepted, as for the previous case.

In all the examples considered, the maximum impact amplitude is assumed to be the same and equal to one.

In Fig. 4 the results obtained for horizontal displacements of w for a point ($H = 325$ m) of a structure in time are given for the following cases: the structure material is linearly elastic without DHA; the structure material is nonlinear viscoelastic without DHA; the structure material is nonlinear viscoelastic with DHA.

In Fig. 4 the results obtained for three cases are presented: the construction material is nonlinear elastic (curve *3*) without taking into account DHA; the construction material is nonlinear viscoelastic (curve *2*) without taking into account DHA; the construction material is nonlinear viscoelastic and the damper is linear viscoelastic (curve *1*). As can be seen from the results (see Fig. 4), during the oscillation process at the beginning of the process, when the displacements are still small, there is practically no difference in amplitudes for the three cases. As the oscillation time increases, taking into account the non-linearly elastic properties of the building material, the oscillation amplitude (curve *3*) increases, and resonance occurs, as in the elastic case. Taking into account the nonlinear viscoelastic properties of the structure also does not allow an increase in the amplitude of vibrations (curve *2*) over time. Installing a damper and taking into account the nonlinear viscoelastic properties of the structure effectively reduces

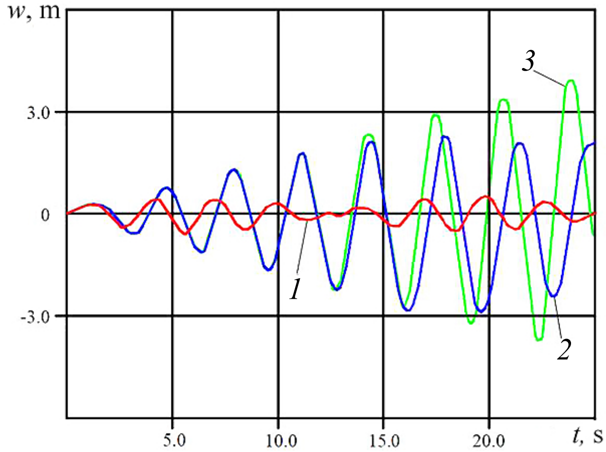

Fig. 4. Changes in horizontal displacements w of a point ($z = 325$ m) of a structure: the structure material is nonlinearly elastic without taking into account the DVD (*3*); the structure material is nonlinearly viscoelastic without taking into account the DVD (*2*); the structure material is nonlinearly viscoelastic taking into account the DVD (*1*) under kinematic action (9)

the level of vibrations of the structure (curve *1*). At the same time, taking into account viscoelastic properties slightly reduces the frequency spectrum of vibrations.

2.3. Fluctuations of a high-rise structure with a DHC, taking into account the elastic-plastic deformation of the building material. In Fig. 5 shows changes in the amplitude of vibrations of the upper point ($z = 325$ m) of the structure (that is, horizontal movements —w) under low-frequency exposure of the type

$$\ddot{w}_0 = \begin{cases} \sin(0.3pt), & 0 \leqslant t \leqslant \dfrac{2\pi}{0.3p}, \\ 0, & t > \dfrac{2\pi}{0.3p} \end{cases} \tag{11}$$

taking into account the elastic-plastic properties of the construction material without taking into account DHA (curve *1*) and taking into account the linear-viscoelastic properties of DHA (curve *2*).

An analysis of the graphs (Fig. 5) shows that taking into account the elastic-plastic properties of the structure's material and with DHA (curve *2*) increases the oscillation period of the structure and

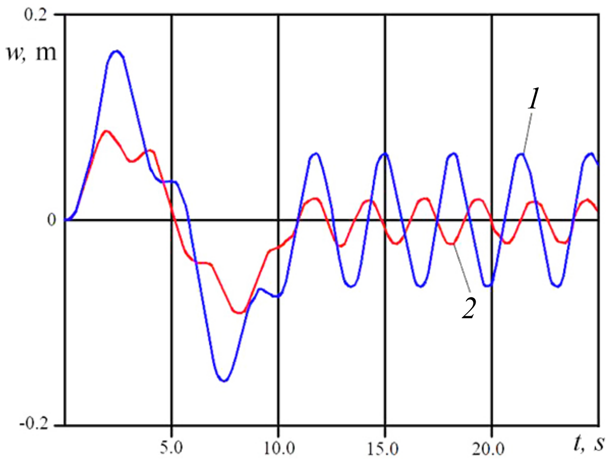

Fig. 5. Changes in horizontal displacements of the top point ($z = 325$ m) of the structure taking into account the elastic-plastic properties of the structure material: without DVD ($- - -$) and with DVD ($- * - * -$) under low-frequency kinematic action (11)

leads to a decrease in the vibration level of a high-rise structure by about half.

Thus, the obtained calculations of a high-rise structure with DHC under various dynamic influences and taking into account the different properties of the structure and DHC material allow us to draw conclusions regarding the effectiveness of using DHC in the operation of high-rise structures in various dynamic modes.

Conclusion

1. The paper provides a detailed overview of well-known works related to the study of the dynamic behavior of a number of high-rise structures with and without high-rise buildings.
2. To assess the dynamic behavior of a structure using DHC, a mathematical model, method and algorithm for solving the tasks are given, taking into account the linear and nonlinear elastic, viscoelastic and elastoplastic properties of the material of a structure with DHC under the action of various kinematic influences.
3. The fluctuations of high-rise structures are studied taking into account the linear, nonlinear elastic, viscoelastic and elastoplastic properties of the structure material with DHC under various kinematic influences near the resonance regime.
4. The effectiveness of damping vibrations of a high-rise structure has been revealed when taking into account the nonlinear viscoelastic and elastoplastic properties of the structure's material in conjunction with viscoelastic DHC.

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