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The Dynamics of the System "Elastic Foundation-High Rise Construction-Dynamic Ring-Type Damper"

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Abstract: The operation of a ring-type damper of linear (in different directions) and rotational oscillations of high-rise tower-base constructions is described in this study. The resolving equations of motion for the proposed model of damper are obtained. The equations of dynamic equilibrium of the foundation slab and individual supports, included in the finite element system "construction damper" are presented. The influence of the finite stiffness of the soil foundation on adjustment and operation of a nonlinear damper of the building is considered. The numerical experiment of the spatial dynamics control of a structure in the system "foundation structure damper" is presented.

Key words: Spatial dynamics, nonlinear model, vibration damper, soil foundation, Russia

INTRODUCTION

The problem of protecting high-rise structures from the development of the amplitudes of the oscillations is solved for many years with the help of special devices called vibration dampers. Structurally similar devices may have different operating principles and circuits (Majewski *et al*., 2004). Dynamic dampers are the most widely used. In the theoretical calculations most of these dampers are represented as one-dimensional model with its bulk. Such a model with one degree of freedom of the bulk describes the motion of the protected structure according to the first form of natural vibrations. This approach is justified only for the planar deformation structures with sparse spectrum of natural frequencies. For the spatial tower-base constructions the two similar perpendicular vectors of liner displacements in mutually perpendicular surfaces and the vector of rotary oscillations correspond to the three lower natural frequencies. As it is known, the ring has three degrees of freedom on its surface and it possesses the advantage over other geometrical figures that the system of radial springs is able to provide invariant conditions of resistance to rectilinear motion and effective operation at winding of a tower. Therefore, for tower-base constructions it is reasonable to apply a ring-type damper (Shein and Zemtsova, 2010). To counteract the beats in the first three frequencies one can select a system of elastic bonds, the diameter and also the mass of the ring. Insertion of additional damping devices into the system of elastic bonds helps to dissipate vibration energy.

For fine adjustment of the damper it is necessary to consider the operation of the construction along with the foundation, as it has a significant impact on the spectrum of natural frequencies of this structure. A spatial model of a high-rise building on elastic foundation is presented in this paper, taking into account the damping in structural elements and soil. This model allows to investigate the oscillations of structures under the influence of wind load, to install and adjust efficiently the nonlinear vibration damper. The motion equations of the structure with regard to the internal damping of the system.

MATERIALS AND METHODS

The motion equation of a mechanical system has the form:

$$M\ddot{U}+B\dot{U}+KU = P(t) \tag{1}$$

Where:

M = The mass matrix
U = The displacement vector
B = The internal damping matrix
K = The stiffness matrix
P(t) = Vector of external load

In case of convergence of the ripple frequency of wind load to the natural frequency of the structure, the phenomenon of beating is observed. For damping resonant vibrations of the structure we introduce the system of the ring-type dynamic damper.

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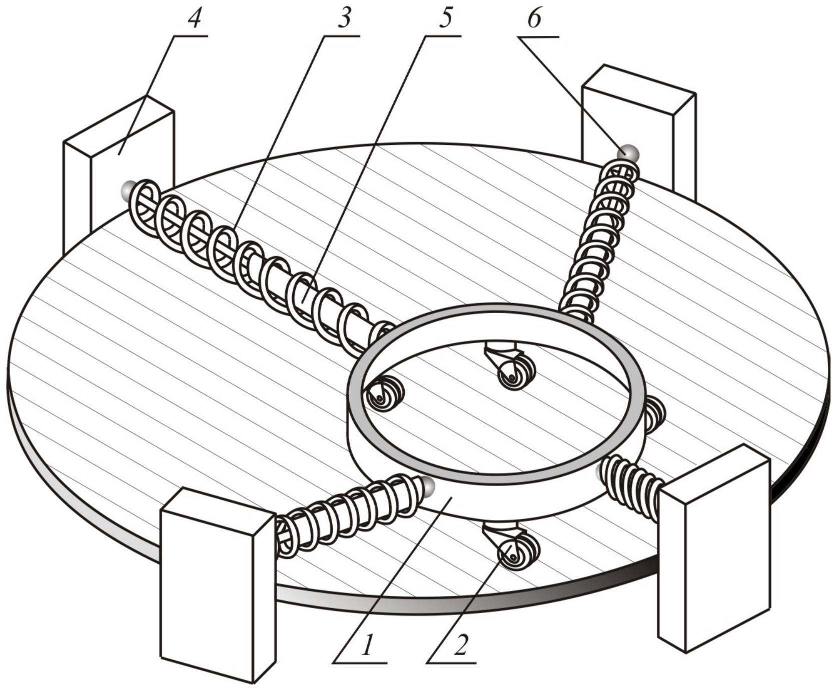

Fig. 1: The structural diagram of a ring-type damper

The ring-type dynamic damper: The authors have developed the ring-type dynamic damper (Fig. 1) which can be adjusted to suppression of the two linear and one rotational resonance oscillations. The design of the dynamic damper (Fig. 1) is made in the form of an annular mass 1. Supporting means of the damper 2 are roller ways. Horizontal springs 3 connecting the mass of a damper with the structure 4 are mounted radially. Vibration absorber is equipped with the viscous friction dampers 5 that increase the damping and prevent significant displacements of the absorber over the top of the building. The dampers are attached to the nodes in the structure by means of spherical bearings 6.

A starting adjustment of the damper is carried out at three low natural frequencies of the structure, corresponding to the longitudinal, transverse and torsional forms of vibrations, by means of selection of the damper mass, the radius of the ring, of spring stiffness and the coefficient of resistance to movement of shock absorbers. The device operates as follows. An accelerated motion of the nodes at the structure 4 is caused by the oscillatory movement of a construction effected by the force of a wind or seismic effects which causes tension and compression of the spring 3 which is accompanied by the moving of the damper mass 1 on the roller bearings 2. Amplitude reduction of the structure oscillations is due to the fact that an elastic force of the spring arising from the damper displacement is directed oppositely to the disturbing effects. Additional energy dissipation of oscillations is provided by the viscous friction dampers 5.

The equations for the coordinates of the ring-type damper (Fig. 2) has the form:

$$U_C^{global,\,ring} = U_M^{tower} + T_M^{tower} \times U_C^{local,\,ring} \quad (2)$$

Where:

$$U_C^{global,\,ring} = \{X_C \quad Y_C \quad \varphi\}^T$$

$$U_M^{tower} = \{X_M \quad Y_M \quad \varphi_M\}^T$$

$$T_M^{tower} = \begin{bmatrix} \cos\varphi_M & -\sin\varphi_M & 0 \\ \sin\varphi_M & \cos\varphi_M & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (3)$$

$$U_C^{local,\,ring} = \{x_C \quad y_C \quad \varphi_2\}^T$$

For the equation formation of motion of the ring-type damper, the expressions for the coordinates of the mounting points of the springs to the ring and the mounting points of the springs to the plate must be written. The equations for the coordinates of the i-th ring points (the mounting points of the springs) have the form:

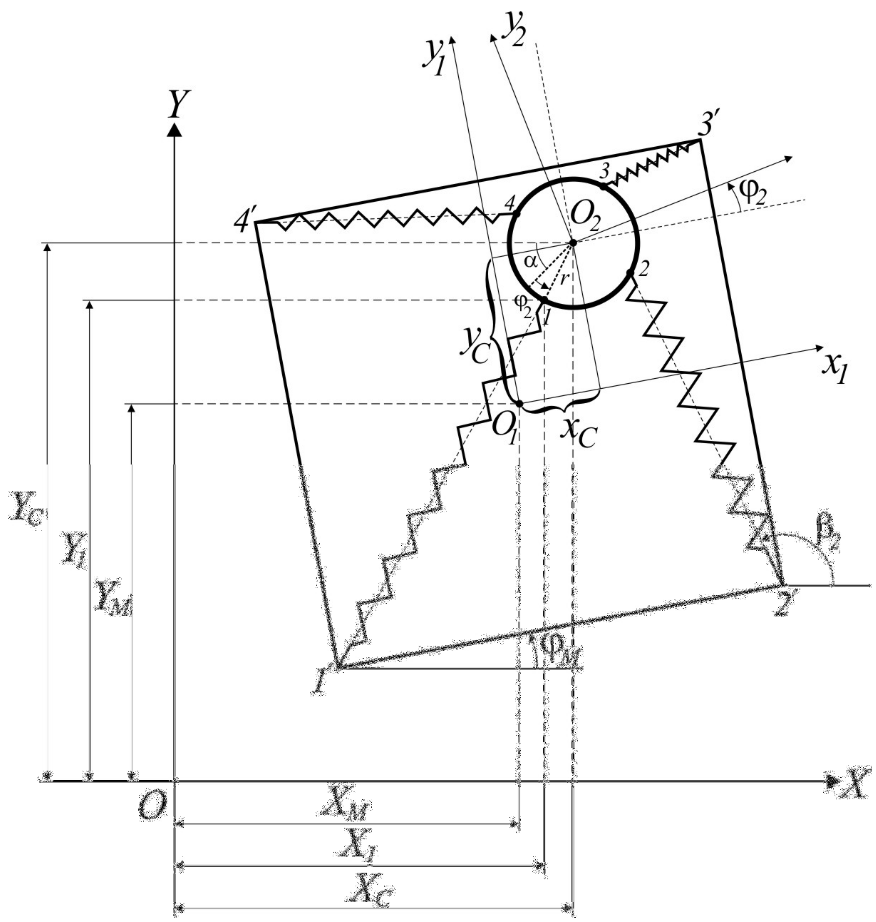

Fig. 2: Mathematical model of the ring-type damper

$$U_i^{global} = U_M + T_M \times U_i^{local} \quad (4)$$

Where it is indicated:

$$U_i^{global} = \{X_i \quad Y_i\}^T$$

$$U_M = \{X_M \quad Y_M\}^T$$

$$T_M = \begin{bmatrix} \cos\varphi_M & -\sin\varphi_M \\ \sin\varphi_M & \cos\varphi_M \end{bmatrix}$$

$$U_i^{local} = \begin{bmatrix} x_C - r\times\cos(a_i+\varphi_2) \\ y_C - r\times\sin(a_i+\varphi_2) \end{bmatrix}$$

The motion equations of the ring-type damper are:

$$M_1 U_C^{global,\ ring} = F^{ring} \quad (5)$$

Where:

$$M_1 = diag\begin{bmatrix} m_1 & m_1 & m_1 r^2 \end{bmatrix}$$

$$F^{ring} = \{F_x \quad F_y \quad M_{Cz}\}^T = \{\Sigma F_{ix} \, \Sigma F_{iy} \; \Sigma M_{iCz}\}^T$$

Here, the mass acceleration of the damper in the global coordinate system:

$$U_C^{global,\ ring} = U_M^{tower} + T_M^{tower} \times U_C^{local,\ ring} + T_M^{tower} \times U_C^{local,ring} + 2\dot{T}_M^{tower} \times U_C^{local,\ ring} \quad (6)$$

At this point, the damper angle of rotation is equal to:

$$\varphi = \varphi_M + \varphi_2 \quad (7)$$

Deduction of the theoretical calculation for soil base: When sufficiently intense dynamic effects and with account of the large difference in the deformation of the slab and the foundation, the bedplate of the tower can be

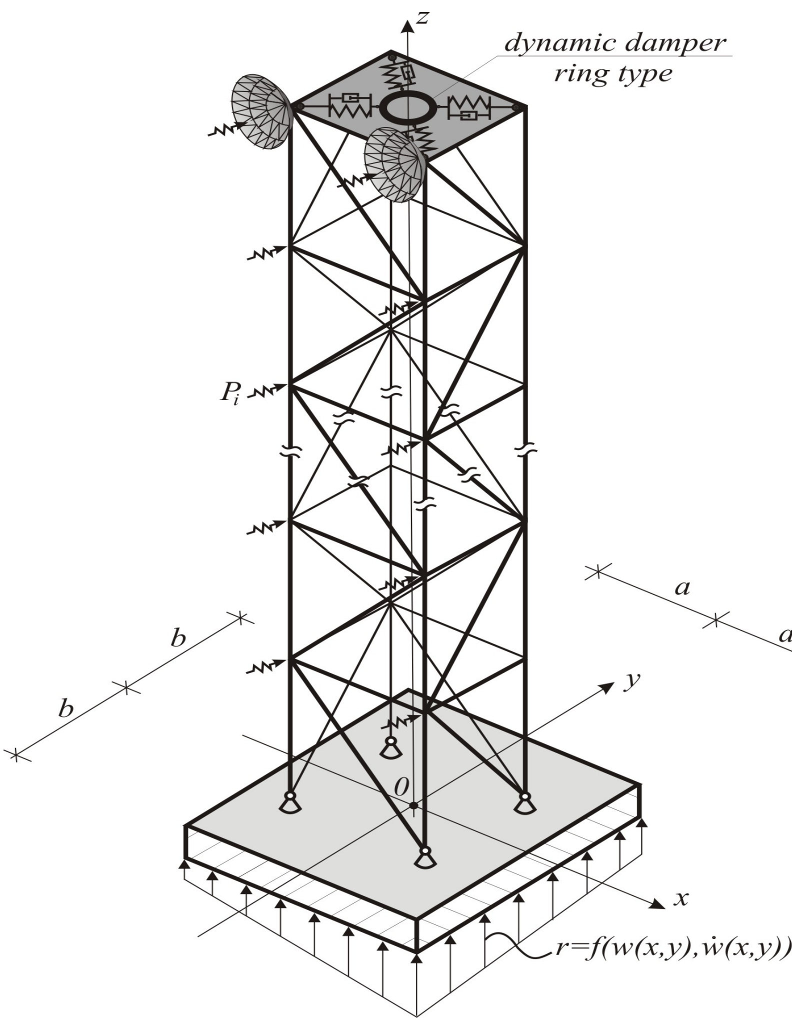

Fig. 3: The model of high-rise construction with the foundation slab on the winkler base

considered as an absolutely rigid body with respect to the soil foundation. We assume that the foundation or the bedding responds elastically under static load in the vertical direction and it is proportional to the vertical displacements of the rigid foundation slab. So, we accept the winkler soil foundation model (Fig. 3). This model is best suited for describing the dynamic operation of the foundation. Moreover, one can easily pass from the Winkler model to the model of nonlinear elastic foundation with rigid or soft elastic characteristics. The terms of dynamic equilibrium of the foundation slab upon an elastic basis can be written as:

$$\left.\begin{aligned} I_x^m\ddot{\varphi}_x+\iint_A r\times y\times dx\times dy &= \sum M_x \\ I_y^m\ddot{\varphi}_y+\iint_A r\times y\times dx\times dy &= \sum M_y \\ m_{plate}\ddot{w}_0+\iint_A r\times y\times dx\times dy &= \sum N_z \end{aligned}\right\} \qquad (8)$$

Where:

$I_y^m\ I_x^m$ = The moments of inertia of the slab mass about the axes x and y, respectively

$\ddot{\varphi}_y\ \ddot{\varphi}_x$ = Angular accelerations of the slab during its rotation around axis x and y, respectively

M_x, M_y = External forces about axes x and y, respectively

N_z = The projections of external forces on the axis z

$\ddot{w}_0$ = Acceleration of the slab in translation along the axis z

m_{plate} = The mass of the slab

r = The intensity of the reaction of the foundation

A = The area of the slab

The dynamic response at the viscoelastic Winkler foundation point can be determined using the following equation:

$$r = k\times w+\alpha\times \dot{w} \tag{9}$$

Where:

k = The coefficient of the layer
w = The vertical movement of the slab point
α = The coefficient of resistance to movement of the soil
$\dot{w}$ = The velocity of the slab point displacement

In this case, the vertical displacement of the slab point is given by

$$w = w_0+\varphi_x\times y-\varphi_y\times x \tag{10}$$

Where:

w_0 = The vertical displacement of the point which in the unconstrained state coincides with the origin
φ_x, φ_y = The slab rotation angles around the axes x and y, respectively

Substituting Eq. 8-10 and integrating, for the principal central axes we will obtain the following:

$$\left.\begin{aligned} I^m_x\ddot{\varphi}_x+I^A_x(k\varphi_x+a\ddot{\varphi}_x) &= \sum M_x \\ I^m_y\ddot{\varphi}_y+I^A_y(k\varphi_y+a\ddot{\varphi}_y) &= \sum M_y \\ m_{plate}\ddot{w}_0+A(kw_0+a\dot{w}_0) &= \sum N_z \end{aligned}\right\} \tag{11}$$

Thus, the system of dynamic equilibrium (Hughes, 1987; Zienkiewicz, 1988) "construction-damper" will expand to three equations with three unknown functions of displacements φ_x, φ_y and w_0. At the same time the movements of the focal points of structures (towers) in the vertical direction u_p from the fixed displacements will go into the variables, associated with the slab ratio of the form Eq. 10. Here, the index p is equal to the numbers of vertical displacements. The matrix rows of the rigidity system "structure-damper" will be supplemented with elements:

$$\begin{aligned} k_{i,(n-2)} &= k_{i,p} \\ k_{i,(n-1)} &= k_{i,p}\times y_l \\ k_{i,(n)} &= k_{i,p}x \end{aligned} \tag{12}$$

Where:

I = The row number (i = 1, 2, 3, ..., n-2)
l = The number of the bearing point corresponding to the movement p
n = The number of unknown displacements in the system "foundation-construction damper"

The rows of damping matrix will change in the same way. When calculating the natural frequencies of the system, it is necessary to keep in mind that the right sides of Eq. 11 are generally speaking, the internal forces. Therefore, in determining the natural frequencies and forms of these equations it is advisable to rewrite them, replace the right parts to the left, at the same time expressing the internal forces through the focal displacements. In some cases, the bases of focal points of high-rise constructions can be executed as being independent of each other. In these cases, the elastic reaction of the base of each foundation is easily determined by the ratio:

$$r_i = A_i(k_i w_i+a_i \dot{w}_i) \tag{13}$$

Where A_i the area of the base of the i-th foundation This notation allows you to simulate the local weakening, or vice versa, the local rigid inclusions of soil foundations.

RESULTS AND DISCUSSION

Experimental part: As a model for research, we will consider a steel tower, fixed on a rigid reinforced concrete slab with dimensions of 5.5×5.5×0.5 m. In plan the dimensions of the tower are 4 × 4 m, the elements are made of steel double corners 100×100×10 mm. The antennae are mounted in the upper tier with spherical surface. The wind pressure on the tower was made in accordance with the recommendations of Building Codes and Regulations 2.01.07-85* "loads and effects". The quiescent load P_{st} was calculated, assuming the action of the wind flow and it is perpendicular to one of the tower faces. The peak value of the fluctuating component P_p was calculated without taking into account the dynamic coefficient ξ. Considering the ripple of wind pressure, the focal load is represented as:

$$P^e_n = P_{st,n}+P_{p,n}\sin(\theta_1 t+\alpha_n) \tag{14}$$

Where:

n = The number of the tier
P_{st} = The static component of the wind load
θ_1 = Pulsation frequency
α_n = The initial phases of the oscillations of the pulsation component of wind flow

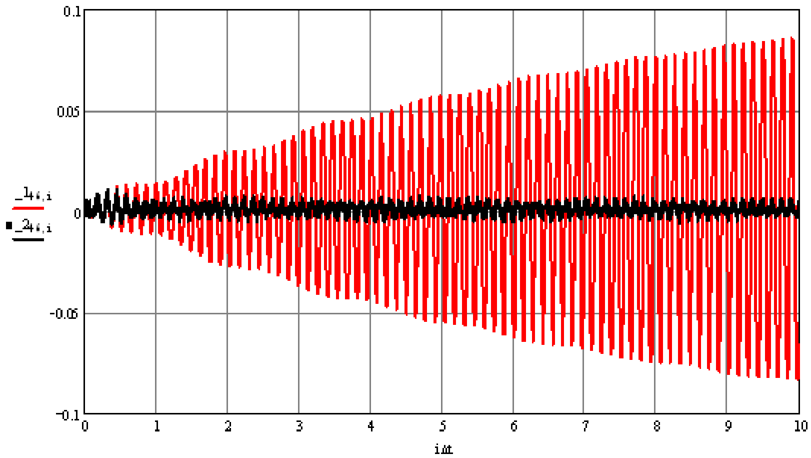

Fig. 4: Constrained oscillations of the top of the tower in the resonant mode (the first frequency) with account of the basement: 1 Without a damper; 2 With a damper

with the help of which you can take into account and model its turbulence and forms according to the natural vibration modes. The initial phases are determined by the corresponding form of the vector of the natural tower oscillations. The first and the second natural forms for the spatial tower-type structure are gradually increasing slopes in one of two mutually perpendicular planes and the third form corresponds to the angular (rotational) vibrations. Such a change in the system specifications makes setting of a damper false without considering the soil type, as the work of the damper in this case is not effective enough.

The firm ground (sand, gravel, crushed stone, clay of low humidity) with coefficient of layer k = 75 MPa/m was taken as the material underlying the surface. The first frequency of the system changed on 11%. The effectiveness of the damper with previously adopted characteristics decreased significantly in this case. To exclude the resonant motion of the tower in the range of the first three natural frequencies, the ring-type dynamic damper with three degrees of freedom can be applied (Shein and Zemtsova, 2010). The adjustment of such a device includes a selection of several parameters: the mass of a damper (m_{damper}), the stiffness ratio of its elastic bonds (c_{damper}), the radius of the moving part (r_{damper}) and the coefficient of tractive resistance of the absorbers (c_{damper}). Taking into account the operation of the basement for damping the oscillations of the first three frequencies, we will accept: m_{damper} = 100 kg, $ñ_{damper}$=100000 N m^{-1}, r_{damper} = 0,3 m, c_{damper}=250 N/(cm/s). Then the displacement time diagram of the upper floor at the coincidence of pulsation frequency of the wind flow with the first natural frequency of the structure will be as follows (Fig. 4).The damper with the selected parameters operates in the same way at the second and third frequencies.

CONCLUSION

The theory and the numerical experiment of the ring-type damper use for tower-base structures are presented in this study. The description of operation and setting of vibration damper is made when incorporated in finite element model, taking into account stiffness characteristics of high-rise constructions and ductility of the soil layer. To show the dynamics of the foundation slab at the soil base the modernized Winkler model is used, with account of the effect of basement on the dynamic behavior of the tower. Efficient operation of the nonlinear ring-type damper is shown.

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