MITIGATION OF RESPONSE OF HIGH-RISE STRUCTURAL SYSTEMS BY MEANS OF OPTIMAL TUNED MASS DAMPERS.

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ABSTRACT

In this paper a passive vibration absorber has been proposed to protect high-rise structural systems from earthquake damages. A structure is modeled by one-mass and n-mass systems (a cantilever scheme). Damping of the structure and absorber installed on top of it is represented by frequency independent one on the base of equivalent viscoelastic model that allows the structure with absorber to be described as a system with non-proportional internal friction. A ground movement is modeled by an actuator that produces vibrations with a changeable amplitude and frequency. In result, modeling of a system behavior under seismic actions is reduced to the passage the latter through resonance. To determine the optimum absorber parameters, an optimization problem, that is a minmax one, was solved by using nonlinear programming technique (the Hooke-Jeves method). A simple and convenient structural tuned mass damper of a pendulum type, that was installed in many stacks, is described.

KEYWORDS

High-rise systems; earthquake actions; optimal tuned mass dampers.

Nomenclature

- $c, (c_j)$ - viscous damping coefficient
- $F(\,)$ - aim function
- $f, (f_j)$ - tuning ratio
- $k, (k_j)$ - spring constants
- k_a - spring constant of an abstract oscillator
- $[K]$ - stiffness matrix
- $m, (m_j)$ - mass
- m_a - mass of an abstract oscillator
- M - mass vector
- $[M]$ - mass matrix
- $u, (u_j)$ - absolute displacement
- u_g - ground displacement
- $\dot{u}_{gmax}$ - maximum ground velocity
- $\ddot{u}_g$ - ground acceleration
- $v, (v_j)$ - relative displacement
- V - relative displacement vector
- t - time
- t_{pr} - duration of the ground shaking
- T_o - initial instantaneous period

T_{max} - final instantaneous period
$[\Phi]$ - modal matrix
$[p]$ - spectrum matrix
$\beta, (\beta_j)$ - mass ratio
ξ - damping ratio
$\omega, (\omega_j)$ - frequency
ω_a - frequency of an abstract oscillator
Ω_1 - frequency of the first natural mode of vibration
ν - frequency of seismic excitation
γ_j - damping coefficient
$[\gamma]$ - damping matrix

Introduction

High-rise structural systems (skyscrapers, communication and TV towers, chimney stacks) are often used in civil engineering practice. Their model can be considered as a flexible cantilever. Usually there is a strong necessity to protect them from vibrations caused by wind and earthquake actions. There are two ways to design them. The first way is to project them strong enough to resist all horizontal loads. The second one is to use vibration absorbers (passive or active) installed in the top part of a system. The latter represents a dynamic support for high-rise structure, and as a result it decreases the dynamic response from horizontal seismic actions (the paper considers only a seismic case). The above-mentioned absorbers can be used for the protection of high-rise structures from earthquake damages, and increase their reliability and life time. Usually damping of a structure is described by the Voight model. It is very convenient to use it but the latter describes internal friction depending on frequency that is not fitted for using it in dynamic analyses of structures. An equivalent model, for one-mass system, is typically used by using the Voight model modification, and is based on such choice of a viscous damping coefficient (c) that ξ ($\xi = c/2\sqrt{km}$) must be constant (for given material). This modification provides the equality of resonant amplitudes in the case of the Voight model and the modified frequency independent damping. For high-rise structural systems with absorbers there is a situation with non-proportional internal friction because various parts of the structure have different values of damping. A model of a n-mass system with arbitrary frequency independent damping was developed by Tseitlin (1994) and can be written in matrix notation as

$$[M]\ddot{U} + [M]([M]^{-1}\cdot[K])^{1/2}[\gamma]\dot{U} + [K]U = P(t) \qquad (1)$$

Modeling of a seismic action is complex enough. There are a few ways to model it: using nonstationar stochastic process, a real time history, and an actuator (with a changeable amplitude and frequency) that was considered in the paper. Its model was developed by Shustov (1976), and imitates a Cone regime per the following formula for one - dimensional horizontal vibrations:

$$u_g = at\sin[2\pi\cdot\log_b[(b-1)t/bT_o + 1]] \qquad (2)$$

where $a = u_{gmax} / \sqrt{1 + (2\pi/\ln b)}$ (3)

$$b = t_{pr} / (t_{pr} - T_{max} + T_o) \qquad (4)$$

Dependence of a displacement and acceleration of the actuator respect to time is shown on Fig.1 and Fig.2

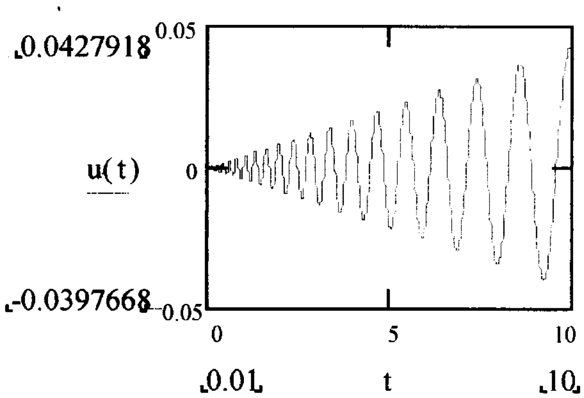

Fig. 1 Imitation regime Cone (displacement).

The application of "Cone" is a heavy model of seismic excitation with a linear changing amplitude, and does not leave any chance for missing a single hazardous frequency. All natural periods of vibrations between T_o and T_{max} (in this paper it was assumed that $T_o = 0.03$ sec and $T_{max} = 2$ sec) are run up in the state of transient resonance. The duration of ground shaking was taken $t_{pr} = 10$ sec, and a maximum velocity was 20 cm/sec.

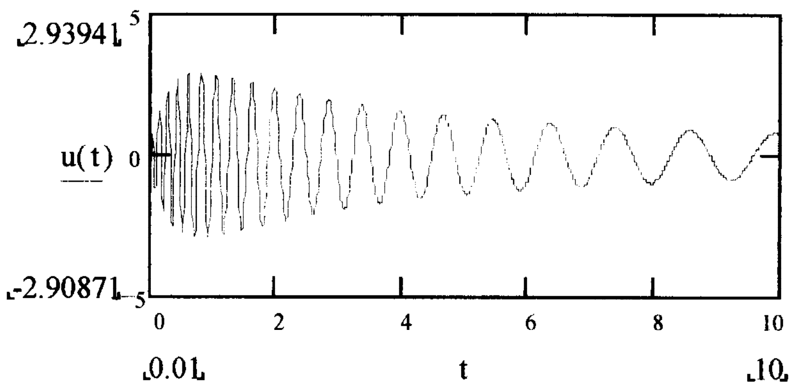

Fig.2 Imitation regime Cone (acceleration).

Analysis of a N - mass system with an associated absorber.

A high-rise structure with an absorber, installed on top part of it, can be modeled by a discrete cantilever as shown on Fig. 3.

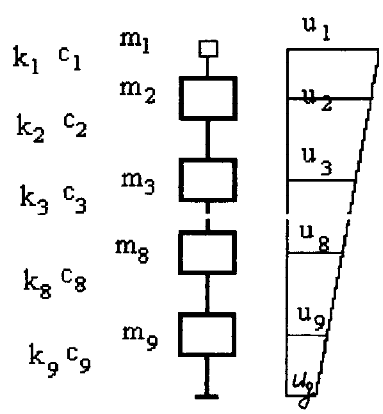

Fig. 3 Parameters of a 8-mass system with an absorber

Using relative displacements ($v_j = u_j - u_{(j+1)}$), the equation (1) can be rewritten as

$$[M]\ddot{V} + [M][\Phi][p][\Phi]^{-1}[\gamma]\dot{V} + [K]V = -M\ddot{u}_g \qquad (5)$$

where $[\Phi][p][\Phi]^{-1} = ([M]^{-1}\cdot[K])^{1/2}$, (6)

$$[M] = \begin{bmatrix} M_1 & M_1 & M_1 & \cdots & M_1 \\ M_1 & M_2 & M_2 & \cdots & M_2 \\ M_1 & M_2 & M_3 & \cdots & M_3 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ M_1 & M_2 & M_3 & \cdots & M_n \end{bmatrix} \quad [\gamma] = \begin{bmatrix} \gamma_1 & \cdots & \cdots & \cdots & \cdots \\ \cdots & \gamma_2 & \cdots & \cdots & \cdots \\ \cdots & \cdots & \gamma_3 & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \gamma_n \end{bmatrix} \quad [K] = \begin{bmatrix} k_1 & \cdots & \cdots & \cdots & \cdots \\ \cdots & k_2 & \cdots & \cdots & \cdots \\ \cdots & \cdots & k_3 & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & k_n \end{bmatrix} \quad M = \begin{bmatrix} M_1 \\ M_2 \\ M_3 \\ \cdots \\ M_n \end{bmatrix}$$

Taking into consideration an abstract oscillator with parameters m_a, k_a, and denoting

$$\omega_a^2 = k_a / m_a,\ \omega_j^2 = k_j / m_j,\ \beta_j = m_j / m_a,\ \mu_j = c_j / 2\sqrt{k_j m_j},\ \gamma_j = 2\mu_j,\ f_j = \omega_j / \omega_a \qquad (7)$$

and having settled on the characteristic length - l, mass - m_a, and time - t, the coordinates and parameters in (5), (6) can be nondimensionalized

$$k_j \to f_j^2 \beta_j,\ a \to a / l\omega_a,\ t \to t\omega_a,\ v_j \to v_j / l, \qquad M_i = \sum_{j=1}^{j=i} \beta_j \Big/ \sum_{j=1}^{j=n} \beta_j \qquad (8)$$

To estimate a n - mass system under earthquake actions, a program was developed on the base of the Runge - Kutta method (language C). Blekherman [1995] showed that analysis of passing through resonance of a high-rise structural system with rare spectrum can be simplified by reducing the system to a one-degree-of-freedom one (by using the quality in kinetic energy of both system). In that case the system with an associated absorber can be reduced to a two-degree-of-freedom one, and the problem of getting optimal absorber parameters can be formulated as following:

$$F(u_1, u_2) = \min_{f_1, \gamma_1} \max_{v} |u_2| \qquad (9)$$

where $f_1 = \omega_1 / \Omega_1$.

The above problem was solved by nonlinear programming technique (the Hooke - Jeeves method). Using described technology, a 8-mass system was analyzed without and with OTMD. The structure had mass and stiffness properties uniform over its height: lumped mass $m_j = 15000$ kg,and stiffness k_j; k_j is chosen so that the fundamental natural vibration period T = 1sec, and $\gamma_j = 0.01$, $t_{pr} = 15$ sec). Comparison of two cases is shown on Fig. 4 (the 8-mass system and the same system with OTMD).

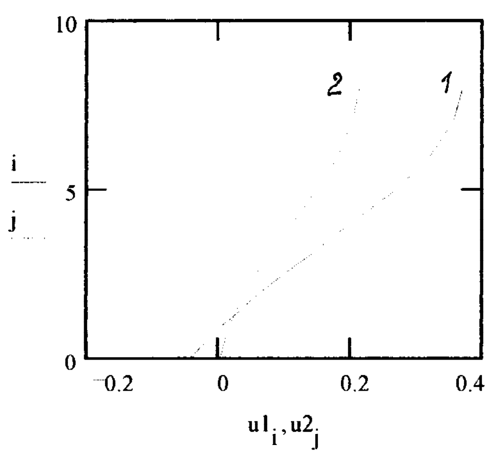

Fig. 4. Comparison of displacements of two systems.
1- 8-Degree-of-Freedom System, 2 - the same system with OTMD

The reduction coefficients is R =0.215m / 0.372m = 0.58. In the considered case, the abstract oscillator is modeled by the first mode of the structure, and $m_{absorber} = 0.05m_a$. The same problem was solved for relative displacements - story drift (by substituting u_i for v_i). Figure 5 displays the comparison of two systems in that case.

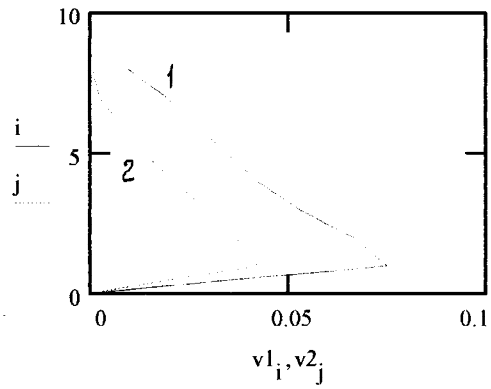

Fig. 5 Comparison of relative displacements of two systems.
1 - 8-degree-of freedom system, 2 - the same system with OTMD.

The first floor has maximum relative displacements in both cases, and the reduction coefficient is R = 0.0425m / 0.075m = 0.567. A full scale problem of the mass system with associated OTMD allows to use the other criteria of quality, for example (overturning moment, base shear and so forth). If the a distance between the first two frequencies is lessened, the dominant mode (in a system with absorber) can become the second one. In that situation (for reaching optimal parameters of an absorber by using a simplified method) it is necessary to reduce the main system to two-degree-of freedom one and use it (together with an absorber) in a minmax problem. In many cases an absorber can be designed with adjusting frequency but fixed nonlinear damping. In that case the problem of optimal tuning ratio (f) is solved with fixed damping. Such absorber was developed for tall stacks by Blekherman and Korenev (1973), and installed in many ones. Figure 6 shows the stack (height 180 m) and Fig. 7 - the pendulum absorber installed in it. The structure of the absorber is a space frame where the absorber mass is attached to the top of the frame by means of steel ropes that is a source of damping. The mass usually equals about 1% - 2% of the whole structure mass. An optimal tuning ratio is adjusted by means of changing the position of an intermediate support device.

Conclusion.

A high-rise structural system with OTMD was considered as the one with nonproportional internal friction. Using OTMD decreases a structural response (displacement, story drift) about two times. The structure, with uniform properies of masses and stiffness, has the most dangerous point on the level of a first story (Fig. 5). A vibration absorber of a pendulum type was described. The installation of the above absorber in many stacks for chemical industry showed the good work of the latter. Besides, the absorber is inexpensive, convenient and simple, and can work in the heavy meteorological conditions.

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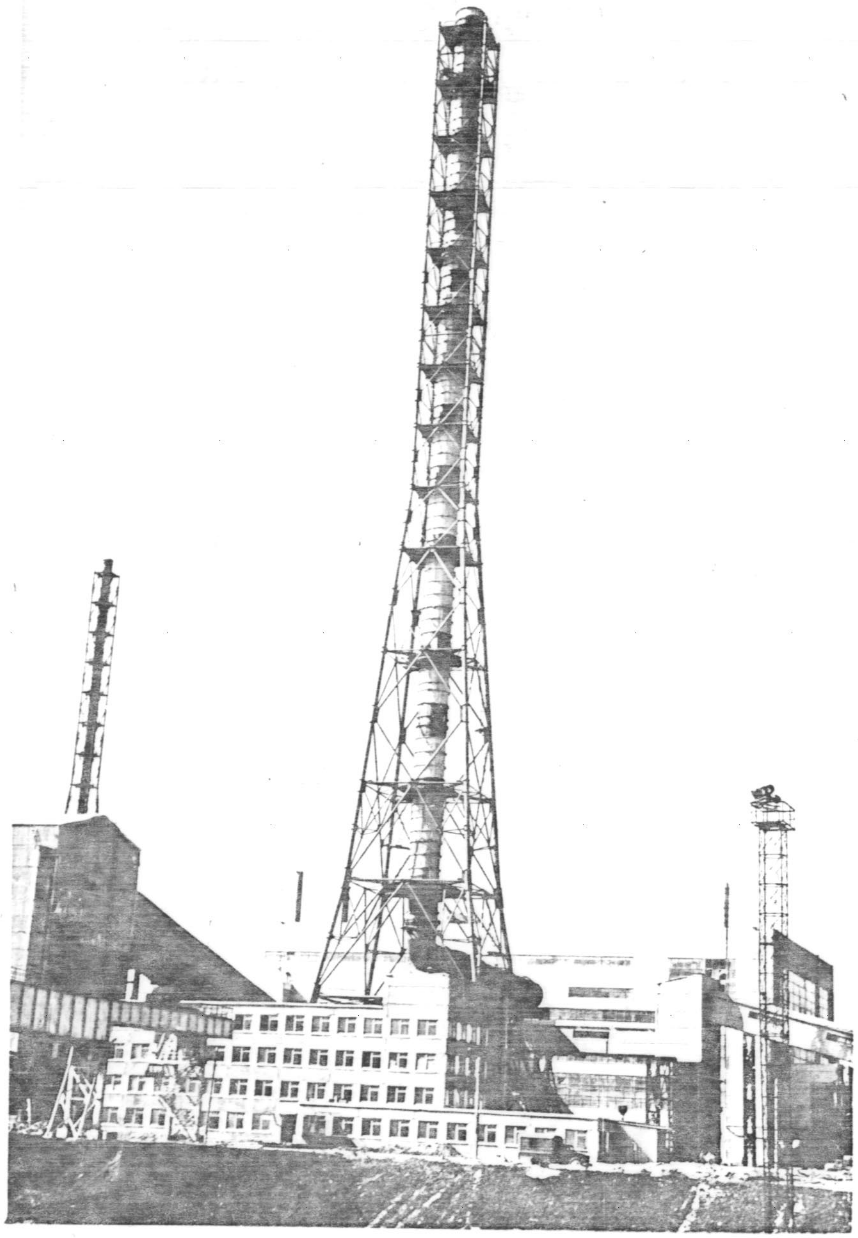

Fig 6.

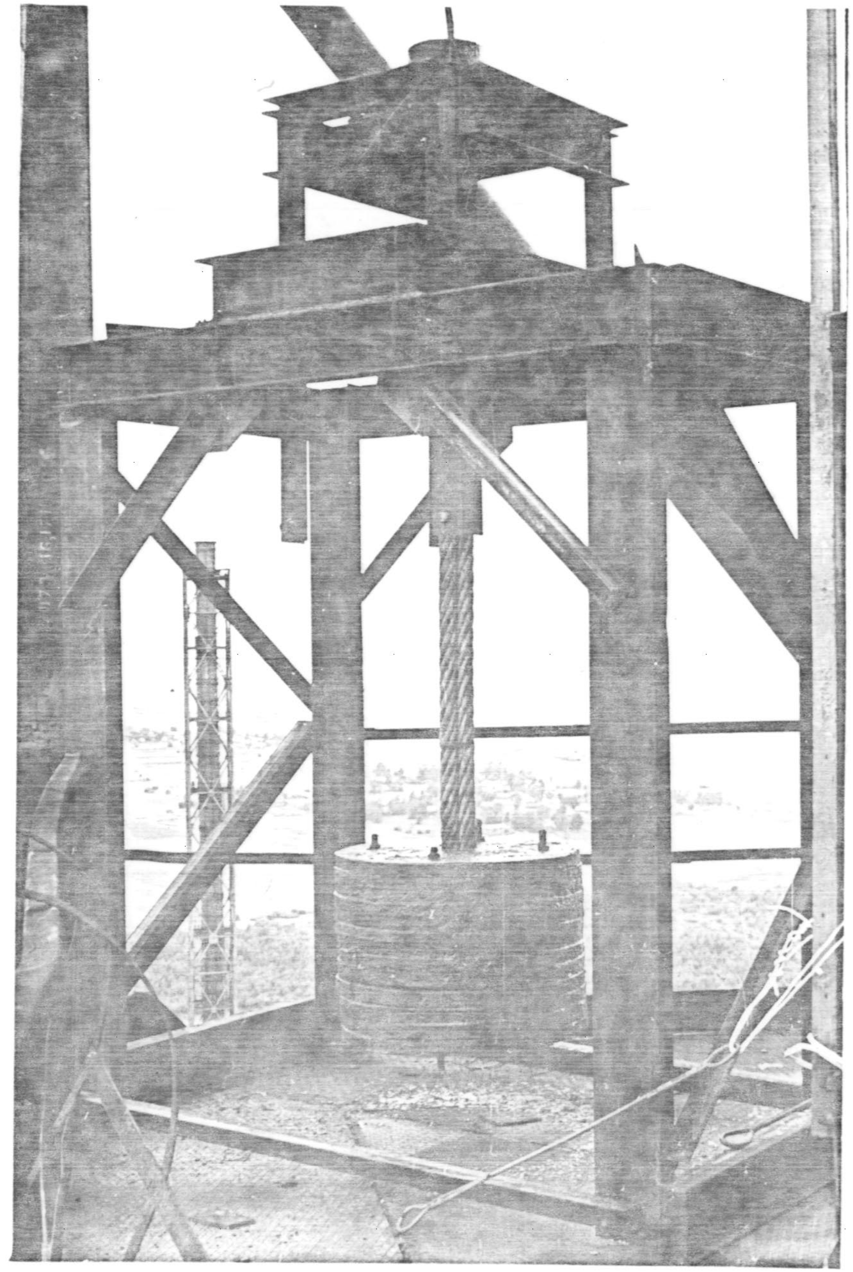

Fig. 7