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Reactive Oscillation Damper of High Rise Constructions under Seismic Load

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Abstract: An active liquid damper as a device for damping vibrations of structures under transient (seismic) influences is considered. The operating principle consists of alternating reactive force formation resisting to relative (flexural) displacement (oscillatory movements) of the structure. The results of the numerical experiment conducted to evaluate the damper efficiency, the choice and settings adjustment are analyzed. The comparison of the liquid reactive damper with the passive three-mass dynamic vibration damper is carried out. According to the results of this comparison, the conclusions about the given dampers efficiency are drawn.

Key words: Active damping, fluid damper, passive vibration damping, a dynamic damper, seismic vibrations

INTRODUCTION

One of the main methods for improving the dynamic strength, stability, durability and reliability of high-rise towers and constructions in seismic regions is applying the systems and devices for damping oscillations. The operation of these systems and devices is largely concerned with the generation of forces impeding to movement or with forces that change the rate of movement (Shein *et al*., 2011; Shein and Zemtsova, 2010, 2012). These forces can have the different physical nature. We introduce the classification of some forces that affect the mechanical system motion and have different physical nature (Table 1).

Table 1: Classification of some forces

Designations of force	Mathematical formula for calculating force
Gravitational force	$m\bar{g}$
Elastic energy	$c\times\Delta\times(t)$
Reactive force	$F_i = V_\Gamma \times dm/dt$
Electromagnetic force	$\partial T/\partial q$
Inertia force (relative force)	$-m\times\bar{a}(t)$
Mtion resistance force	$-\alpha\times v(t)$

In Table 1, the following symbols are used: m is inertia mass of the body; c is stiffness of the elastic system; Δ is displacement of the elastic system; V_Γ is velocity of gas effusion out of the nozzle of the reactive device; T is magnetic field energy; q is electromagnetic drive clearance; a is material point acceleration; α is coefficient of traction resistance; v is velocity of a point system motion.

The operation of pendulum oscillation dampers is carried out by a combination of two forces-gravitational and inertia forces. The operation of single mass and multi mass dynamic vibration dampers of spring-type is based on the combination of the elastic and inertia forces. The vibration dampers of punch-type have pendulum or spring system and they convert instantly the impact energy into the momentum of the elastic force. Antivibration devices use the forces of viscous friction for energy fluctuation dissipation. The above-mentioned vibration dampers are typically used for passive controlling the dynamics of structures or machine parts.

Reactive or electromagnetic forces can be used for development of active vibration dampers. Active vibration dampers can be divided into two main types: the control systems for properties of passive damping; the systems in which the controllable power of active damping is created. We consider the active dampers of the second type.

MATERIALS AND METHODS

The motion equations of structures with dampers under seismic excitation: The movement of a building or a structure under seismic loads can be divided into transferred and relative components. In this case, the structural deformation is caused by the relative movement component. The dynamics of the mechanical systems with reactive damper, subjected to kinematic influences is described by the matrix finite element equation of oscillatory motion:

$$M\ddot{U} + B\dot{U} + KU = -M\ddot{\Delta} + F \quad (1)$$

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Where:
B = The damping matrix
U = The vector of relative displacements (caused by deformation)
$\ddot{\Delta}$ = Transferred (seismic) acceleration
F = The vector reactive effects

$$F = \{0 0 0 ... \pm F_{iu} \pm F_{iv} \pm F_{i\varphi} 0 0 ... \pm F_{ku} \pm F_{kv} \pm F_{k\varphi} 0 ... 0\}^T \tag{2}$$

here, F_i is the reactive force or pair of forces, acting in the line of u, v or in φ at the level of ith floor slab of the building:

$$F_i = V_\Gamma \times \frac{dm}{dt} \tag{3}$$

To illustrate the operation of a reactive damper under seismic loads, we use a liquid damper operating in the opposite direction to relative flexure. Here with an effort that counteract the combined inertia force of relative motion must be developed. The creation of the necessary resistance efforts to the bending after seismic shock can be performed by using the reactive force of water jet flowing from the tank.

We consider the hydraulic system rigidly connected with the ith level of the construction (Fig. 1). The liquid in the tank is under the effect of the excessive (exceeding the atmospheric) pressure p_0. The container is equipped with two quick-opening valves located at the bottom of the tank opposite each other.

When opening the right valve (Fig. 1) through a hole of the sectional Area (A_0) at the time dt, the pulse d(mv) goes where:

$$dm = \rho A_0 v \times dt \tag{4}$$

the flowing liquid mass with density ρ in the time dt, v is the jet velocity determined by the Bernoulli Equation. Thus, on the part of the flowing liquid, the opposite in direction force F_i will effect (Strelkov and Mechanics, 1975; Shein and Shmelev, 2013) on the capacity and the construction:

$$F_i = 2A_0(p_0 + \gamma h) \tag{5}$$

Where:
γ = The specific weight of the fluid
h = The height of the liquid column above the hole

At alternate opening (closing) of the opposite valves, the alternating reactive force will appear, impeding the relative (oscillatory and flexural) displacements of structures. We note that to retain the value of the reactive

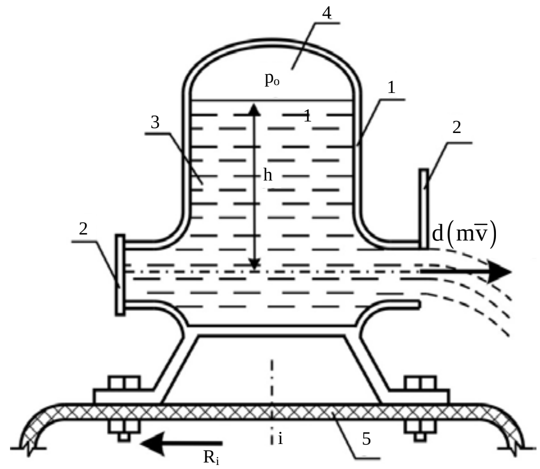

Fig. 1: The scheme of an active liquid damper operation: 1 is capacity of a damper; 2 is a valve; 3 is machining fluid; 4 is pressurized gas; 5 is a protected construction

force, the sustaining of the overpressure p_0 must be allowed. This problem can be solved by the installation of high-pressure cylinders on a container of liquid. Moreover while the numerical investigation of oscillations, it is easy to consider the fact that the mass value of the damper is variable.

The reactive power value can be controlled by changing the sectional area of the outlet openings and the excessive pressure in the tank. The damper of this type is ecologically innocuous and very effective under short and medium-duration effects. The capabilities to control the value, the direction, the moment of time and the period of activation of the reactive force make the reactive dampers particularly effective under non-stationary disturbances such as seismic loads. One disadvantage of an active liquid damper is its relatively high initial weight and the time required for opening and closing water flow valves. The reactive damper, based on the reactive facilities in which the reactive charge systems are rigidly connected with the central load-bearing core of building, doesn't have that disadvantage.

Numerical experiment (Harmonic perturbation): We consider the operation of the liquid reactive damper under the kinematic vibration influences of the tower (Fig. 2). The structure under study is a spatial girder in the form of 30 m-high tower (10 tiers of 3 m) and the width is 2.1 m. The girder has the form of hinged immovable support. The cross-section of all the elements is square tube of 89×5 mm (Fig. 2). The mass of the structural parts "draws together" into the nodes of spatial girder. The mass of the whole structure including its structural elements and the equipment weight that is installed on the top is equal to 9170 kg. The mass of the damper decreases with the fluid consumption. Seismic loading was modeled in the form of foundation vibrations arising from the law of sines:

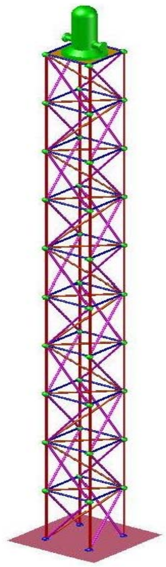

Fig. 2: Exterior view of the constructio with the built-in damper

$$\Delta(t) = f \times \sin(\omega \times t) \quad (6)$$

Where:

ω = The oscillation frequency

A = The oscillation amplitude

The main characteristics of seismic loading were accepted based on the analysis of records for the earthquakes occurred. In this case, the peak acceleration $|f\omega^2|$ does not exceed the magnitude of the acceleration due to gravity (g). The seismic load was applied along the axis of the holes of the damper (X-axis).

The time influence of opening (closing) of the damper valves on the magnitude of the tower displacements was studied. The activation of one or the other valve depended on the symbol of fluctuation velocity of the upper construction units. It was assumed that for the valve T_{op} opening (closing) period of time the reaction force increases (decreases) monotonously, proportionally to the operating time of the valve (Fig. 3).

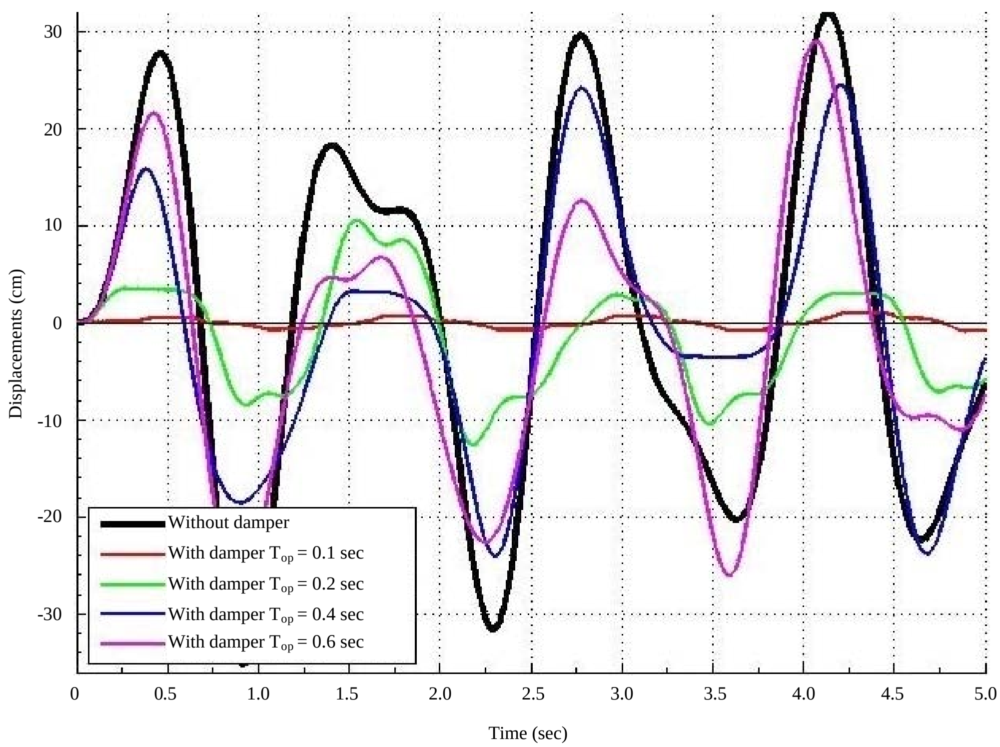

Fig. 3: A comparison of displacements depending on the valve opening time, the diameter of a hole is 0.15 m, the overpressure is 5.5 atm

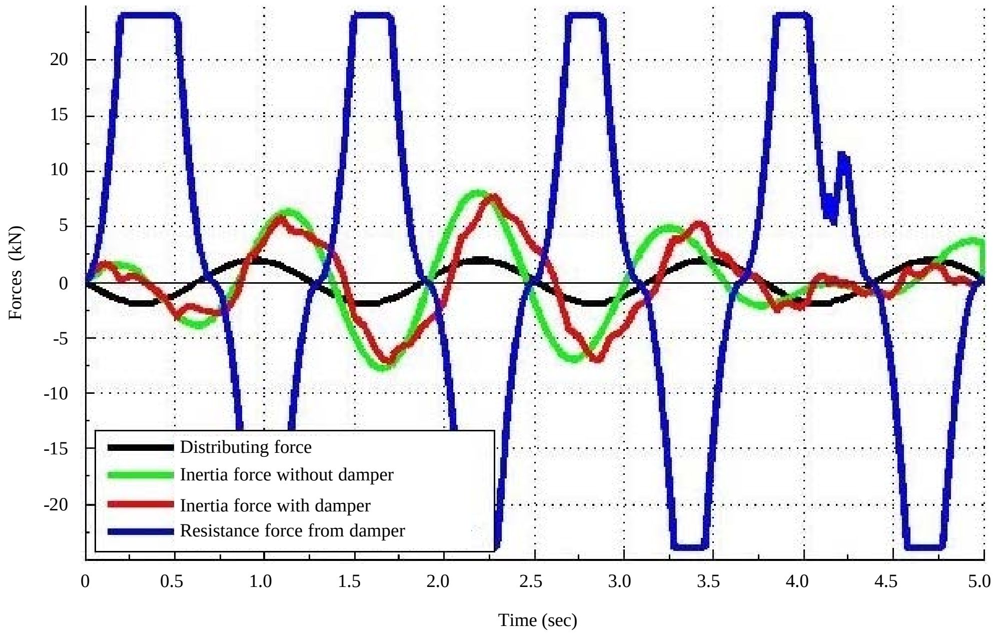

Fig. 4: A comparison of the forces acting on the structure

The damper was accepted with the valve hole diameter of 0.15 m, an excess pressure of 5.5 atm. It was determined that the efficiency of damper is inversely proportional to the time of opening (closing) of the valves (Fig. 3).

The balance of forces influencing upon the structure, namely, the upper unit under the same the disturbing effects was studied. The damper with the diameter of 0.1 m, the overpressure of 15 atm, the time of opening (closing) of the valves -0.2 sec, the initial weight of 2169 kg, was chosen for the exposition. The assumed frequency of the seismic load was equal to 5 sec^{-1}, the amplitude of acceleration was 5 m/c^2. The results of the study are presented in Fig. 4.

RESULTS AND DISCUSSION

Numerical experiment (non-stationary perturbation): Seismic loading was set as the basement oscillations, modeled according to the accelerograms of the following earthquakes (they are arranged in line with the seismic effect duration): the earthquake in Petrolia (California, USA, April 1996), the duration is 10 sec; the earthquake in Naghan (Iran, April 1977), the duration is 5 sec; in San Francisco (California, USA 1957), the duration is 2.5 sec; in Brawley (California, USA 1975), the duration is 2.4 sec.

The overpressure of the liquid damper was held constant and also the of the pressure reduction from a liquid column over the hole was compensated. In experiments, the operation of a three-mass dynamic damper (Fig. 5) and a liquid reactive damper was compared.

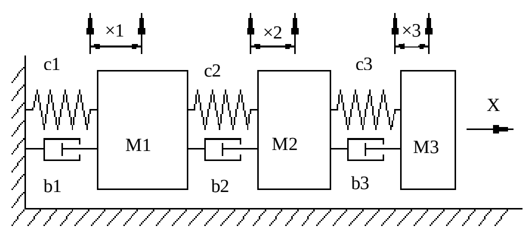

Fig. 5: Scheme of a three-mass dynamic damper

The horizontal displacements of one of the four upper structure units are represented in the calculation results. The following parameters of dampers are accepted in the numerical experiments: a three-mass dynamic vibration damper. The total mass of the damper is equal to 1/15 (7%) of the structure mass. The mass ratio of the damper is $m_2/m_1 = 0.2$; $m_3/m_1 = 0.02$; an active fluid damper. The initial mass of the damper was equal to 17% of the structure mass. The orifice areas of the valves are 100 cm^2. The opening (closing) period of the valves is 0.02 sec. The several overpressure variants in the tank of the damper was investigated.

Research No. 1: The earthquake in Petrolia, from the results of the study (Fig. 6), we notice that the maximum displacements of the structure without dampers exceed

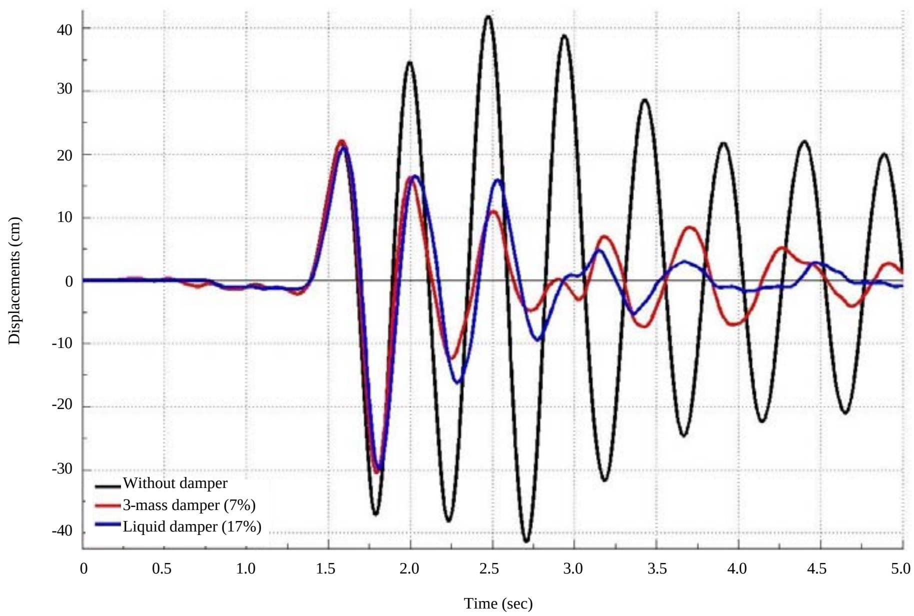

Fig. 6: A comparison of the efficiency of passive and active vibration dampers by the earthquake accelerogram in Petrolia

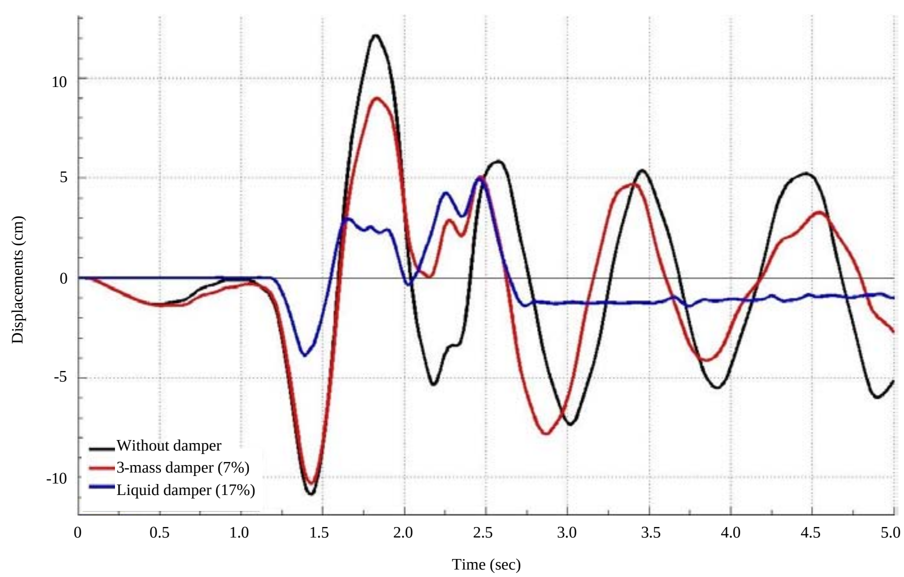

Fig. 7: A comparison of the effectiveness of passive and active vibration dampers by the earthquake accelerogram in Naghan

40 cm. The arranged dampers reduce these displacements by half, up to 20 cm. In this case, both dampers allow the construction to perform only the first two significant oscillations, then the oscillations of the structure are reduced. Herewith, the operation of an active fluid damper is more efficient than the operation of a passive three-mass dynamic oscillation dampers in the last third part of the time of the earthquake. It may be concluded that the both types of dampers fit to prevent this type of earthquake but an active damper is preferable to a passive one.

Research No. 2: The earthquake in Naghan (Fig. 7). From the results of the study, we notice that the maximum displacements of the structure without dampers exceed 12 cm. Both dampers reduce these displacements.

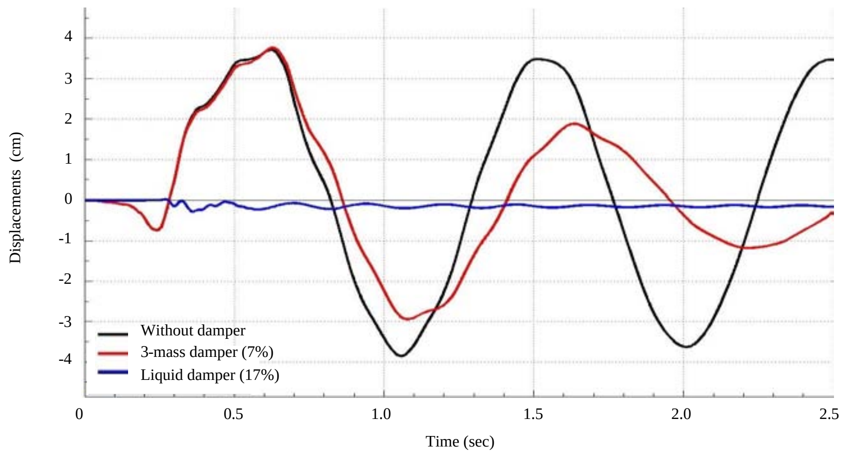

Fig. 8: A comparison of the effectiveness of passive and active vibration dampers by the earthquake accelerogram in San Francisco

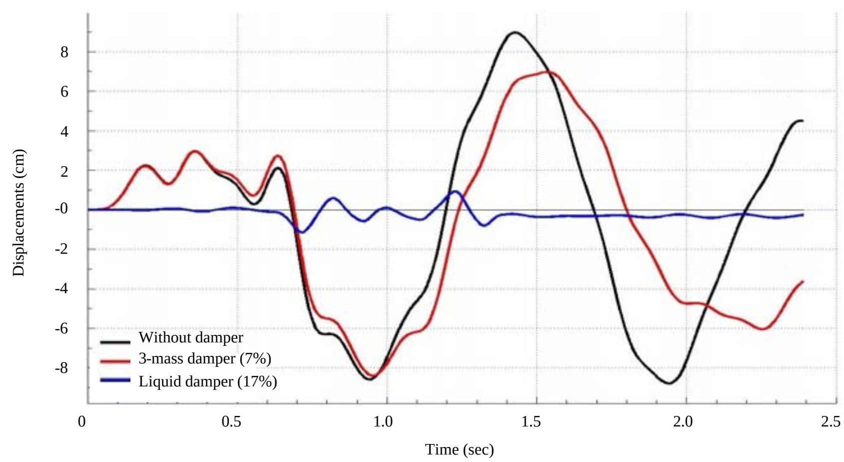

Fig. 9: A comparison of the effectiveness of passive and active vibration dampers by the earthquake accelerogram in Brawley

Herewith, an active liquid damper operates more efficiently than a passive three-mass dynamic oscillation damper. It activates more quickly and reduce the maximal displacements of the structure more than twice: up to 5 cm in the first half of the earthquake period of time and it nearly reduces the displacements to zero in the second half the period. Herewith, a passive damper reduces the maximal displacements of the structure slightly. It may be concluded that to prevent this type of earthquake an active vibration damper is more suitable.

Research No. 3: The comparison of the vibration dampers was carried out according to the earthquake accelerograms in San Francisco with its duration of 2.5 sec (Fig. 8). From the results of the study, we notice that the maximal displacements of the structure without dampers reach up to 4 cm. The installed dampers reduce these displacements. Herewith an active liquid damper operates much more efficiently than a passive three-mass dynamic oscillation damper. It activates instantly and nullifies the displacements of the structure. In this case, a passive damper reduces the maximal displacements of the structure twice. A passive damper activates after the first significant fluctuation and its operation becomes effective before the completion of the earthquake. It may be concluded that to prevent this type of earthquake an active vibration damper is more suitable.

Research No. 4: The comparison of the vibration dampers was carried out according to the earthquake accelerograms in Brawley of the duration in 2.4 sec (Fig. 9). From the results of the study, we notice that the maximal displacements of the structure without a damper are 9 cm. And the installed dampers reduce these displacements. An active liquid damper is much more effective than a passive three-mass dynamic oscillation dampers. It activates immediately and reduces the maximal displacements of the structure by up to nine times, almost reducing it to zero. In this case, a passive damper reduces the maximal displacements of the structure insignificantly. We can conclude that to prevent this type of non-stationary effects an active vibration damper is more suitable.

CONCLUSION

The set of numerical experiments were performed to evaluate the effectiveness of active liquid dampers in non-stationary conditions. And the comparison of the operation of an active liquid damper with the three-mass dynamic oscillation damper was carried out. We can draw the following conclusions on the basis of the conducted research: an active passive damper is much more effective by all the used accelerograms; an active damper activates almost instantly. Therefore, the active damper is the most effective while the earthquakes of short duration, when the maximal displacements of structure arise almost immediately after the initiation of the earthquake. The conducted research confirms that reactive oscillation dampers (in particular liquid dampers) may be the effective means to prevent seismic vibrations.

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