Damping vibrations of an underground structure using a three-mass damper

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Damping vibrations of an underground structure using a three-mass damper

A Abduvaliev[1], and A Abdulkhayzoda[2*]

[1]Tashkent Institute of Irrigation and Agricultural Mechanization Engineers, 100000 Tashkent, Uzbekistan
[2]Tashkent Transport University, Tashkent, Uzbekistan

[*]Email: Abdulaziz_777_7@mail.ru

Abstract. The state of a rigid disk at elastic waves diffraction on it and the possibility of its oscillation suppression using a multi-mass damper was studied in the paper. The operation of a three-mass dynamic oscillation suppression was considered and its application was compared with the operation of a two-mass damper. The effectiveness of the use of multi-mass dampers was estimated by the relative amplitude of disk oscillations and by the width of the frequency zone. It was stated that to suppress disk oscillations in a state of low instability of external impact frequency, the use of single- or two-mass dampers was sufficient. To reduce the disk displacements at unstable frequency of external impact (to cover a wider frequency zone), it is necessary to use a three-mass damper; the width of the damper effective operation significantly increases (about 4-5 times) compared to the operation of a two-mass damper.

1. Introduction

In [1], the oscillation in the elastic space of an underground structure (hard disk) during diffraction of elastic harmonic waves on it is considered. In [2], the dynamic behavior of the soil was studied, and in [3, 4, 5], the stress state and dynamic characteristics of earth dams under various dynamic influences were investigated. Wave processes in determining the mechanical characteristics of the soil are considered in [6, 7]. Oscillation of an elastic half-space with a cylindrical cavity under the action of Rayleigh waves is considered in [8]. Vibrations of a rigid cylindrical disk in elastic space are studied in the article [9].

Since it is important to reduce the vibration amplitude of structures, in [10] the possibilities of reducing the vibration amplitude of a shallow underground structure from the action of Rayleigh waves are considered, in [11] - the possibility of reducing the vibration amplitude of a deeply buried underground structure from the action of elastic waves. The effectiveness of a shock absorber with bending vibrations of straight rods was studied in [12]. The effectiveness of the use of multi-mass dynamic vibration dampers under harmonic external influences was studied in [13, 14, 15, 16, 18]. The efficiency of using a two-mass dynamic damper under a periodic impulse disturbance was investigated in [17], and in [19, 20], the possibilities of damping the vibrations of chimneys and high-rise buildings using multi-mass dynamic absorbers were considered. In all these works, the effectiveness of the use of multi-mass vibration dampers is noted.

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The use of multi-mass dynamic vibration dampers to reduce the amplitude of displacements of underground structures is interesting and relevant.

In the practice of underground structures construction, various structural designs (transport, communication, etc.) are used, mostly of annular or circular cross section. Underground transport structures (tunnels), depending on the intensity of road traffic, have a diameter of 10 m to 18 m, the thickness of the bearing part - 0.4 - 1 m. Such structures can be located at different depths from the ground surface. There are underground structures of shallow laying located at a depth H of 10-12 m, and of deep laying at H> 12 m.

Communication underground structures are mostly of annular cross section. In practice, the designs made of different materials (ceramic, metal, concrete, reinforced concrete, asbestos, plastic) and of different diameter are used. As a rule, the operating underground structures have a sufficiently rigid cross section, which allows their sections consider as undeformable ones in calculations.

Dynamic effects on structures buried in soil are caused by various sources, some of them are of industrial origin, others are the influence of transport operation. So, when trains pass through tunnels, vibrations occur and the wave effect affects nearby underground and ground buildings and structures. Or vice versa, dynamic operation of certain ground-based industrial equipment (hammers, crusher, etc.) causes the vibration of underground structure, and, when located in the vicinity, adversely affects its operating mode.

In order to avoid vibration propagation resulting from the cars motion in tunnels to the neighboring buildings and structures, underground structures must have an increased vibration absorption. Sometimes it is necessary to protect the structure itself from external influences.

The article proposes one of the most effective and reliable measures to protect the structure from various kinds of dynamic effects – oscillation suppression using multi-mass dynamic vibration dampers. A comparison of single-mass, two-mass and three-mass dampers operation was carried out.

The rigid disk oscillation suppression at elastic harmonic waves diffraction on it was considered in [1], where it was shown that by attaching a conventional single-mass vibration damper, a significant damping effect could be achieved. The use of multi-mass dampers to suppress oscillations of a system with one or two degrees of freedom significantly increases the damping efficiency and extends the frequency range in which the use of a damper is appropriate [2].

2. Methods

In this paper, the influence of a multi-mass damper is considered in the graphs of the frequency response characteristic (FRC) of the system. The maximum ordinate of the frequency response is the criterion for the suppression effectiveness. Attenuation in dampers is taken into account according to the Voigt theory (Figure 1).

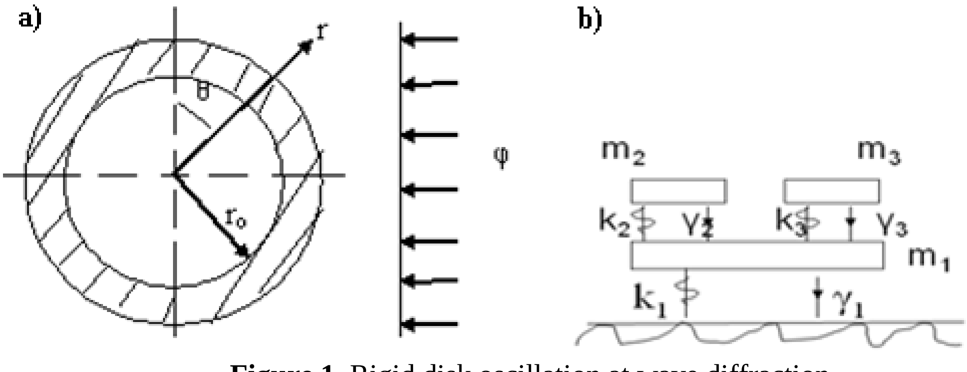

Figure 1. Rigid disk oscillation at wave diffraction

The system of differential equations of disk vibration equipped with a three-mass vibration damper has the form

$$\begin{cases} m_o \frac{d^2 u}{dt^2} + m_1 \frac{d^2 u_{d1}}{dt^2} + m_2 \frac{d^2 u_{d2}}{dt^2} + m_3 \frac{d^2 u_{d3}}{dt^2} = \int_0^{2\pi} [\sigma_r \cos\theta - \tau_{r\theta} \sin\theta] e^{i\omega t} r d\theta, \\ m_1 \frac{d^2 u_{d1}}{dt^2} + m_2 \frac{d^2 u_{d2}}{dt^2} + m_3 \frac{d^2 u_{d3}}{dt^2} + \gamma_1 (\frac{du_{d2}}{dt} - \frac{du}{dt}) + k_1 (u_{d2} - u) = 0, \\ m_2 \frac{d^2 u_{d2}}{dt^2} + \gamma_2 (\frac{du_{d2}}{dt} - \frac{du_{d1}}{dt}) + k_2 (u_{d2} - u_{d1}) = 0, \\ m_3 \frac{d^2 u_{d3}}{dt^2} + \gamma_3 (\frac{du_{d3}}{dt} - \frac{du_{d1}}{dt}) + k_3 (u_{d3} - u_{d1}) = 0, \end{cases} \quad (1)$$

where m_o, m_1, m_2, m_3 are the masses of the disk and the dampers, respectively,
$u, u_{d1}, u_{d2}, u_{d3}$- are the displacements of the disk and the dampers, respectively,
σ_r, $\tau_{r\theta}$ - are the normal and shear stresses of the medium at the side surface of a cylindrical structure,
r_o is the radius of the disk cross section.
Omitting the intermediate calculations, represent the displacement of the disk with a damper in the form

$$u = [\frac{4}{\pi} m H^{(2)}_2 (m\alpha)]/\alpha\{[H^{(2)}_2 (\alpha) H^{(2)}_1 (m\alpha) + m H^{(2)}_2 (m\alpha) H^{(2)}_1 (\alpha)] (1-c) + \\ + m\alpha H^{(2)}_2 (\alpha) H^{(2)}_2 (m\alpha) c\}, \quad (2)$$

where $H^{(2)}_n (z)$ is the Hankel function of the second kind;

$$m = \frac{c_1}{c_2}, \ \alpha = \frac{\omega r}{c_1},$$

c_1, c_2 are the velocities of longitudinal and transverse waves,
b is the ratio of the disk linear mass to the reduced mass of soil, determined by the formula

$$b = \frac{m_0}{\rho r_o^2},$$

ν_1, ν_2, ν_3 are the relative masses of the primary and secondary dampers,

$$C = \frac{b}{\pi} [1 + \nu_1 (A_1 + A_2 \cdot \nu_2 + A_3 \cdot \nu_3)],$$

$$\nu_1 = \frac{m_1}{m_0}, \ \nu_2 = \frac{m_2}{m_1}, \ \nu_3 = \frac{m_3}{m_1}, \ f_1^2 = \frac{k_i}{m_i \ \omega_0^2}, \ \mu_i = \frac{\gamma_i}{m_i \ \omega_0^2},$$
$$A_1 = (f^2_1 + i\mu_1 q)/\{[U_1 - (\nu_2 U_2 + \nu_2 U_2)q^2] + i[\nu_2 V_2 + \nu_3 V_3] q^3 \},$$
$$A_2 = A_1(U_2 - iV_2), \quad A_3 = A_1(U_3 - iV_3), \quad U_1 = [(f_1^2 - q^2) + i\mu_1 q],$$
$$U_2 = [(f_2^2 - q^2) f_2^2 + (\mu_2 q)^2]/[(f_2^2 - q^2) + (\mu_2 q)^2],$$
$$V_2 = \mu_2 q^3/[(f_2^2 - q^2)^2 + (\mu_2 q)^2], \quad (3)$$
$$U_3 = =[(f_3^2 - q^2) f_3^2 + (\mu_3 q)^2]/[(f_3^2 - q^2) + (\mu_3 q)^2],$$
$$V_3 = \mu_3 q^3/[(f_3^2 - q^2)^2 + (\mu_3 q)^2],$$

here f_1, f_2, f_3 –are the oscillation frequencies of masses m_1, m_2, m_3, respectively.

When optimizing the parameters of vibration dampers, the structure parameters are considered constant; the damper parameters f_i, μ_i will be optimized. The width of the resonance zone is taken within α = 0.05 - 0.40, which simplifies the optimization of the dampers parameters.

3. Results and Discussion

In the case of a single-mass damper (ϑ_1=0) with broadband optimization, the resulting effect is negligible. So, at b =10, ϑ_1=0.01- 0.10, the efficiency coefficient is K_e=1.03, and at b =20, ϑ_1=0.01-0.10, Ke = 1.02-1.06, respectively. To achieve a greater damping effect, the frequency range should be reduced, i.e. to conduct optimization not over the entire frequency domain, but only over some part of it, near the resonance zone (Table1).

Table 1. Damper Optimization Results

b	$\boldsymbol{\vartheta_1}$	Optimal parameters		Damping coefficient, K_e
		f_1	μ_1	
10	0.05	0.998	0.192	1.04
	0.10	0.997	0.192	1.08
20	0.01	0.99	0.190	1.02
	0.05	0.984	0.160	1.08
	0.10	0.989	0.144	1.18

The table shows that the damping coefficient K_e is 3-4 times greater than in the broadband version, in which the selected parameters of the damper (f_1, μ_1) depending on b and ϑ_1 have a fairly wide range of variation (f_1 = 0.98 – 0,998, μ_1= 0.14 – 0.19). The so-called narrow-band version makes it possible to damp the disk oscillations in the resonance zone, i.e. at a small deviation of the impact frequency from the frequency of natural oscillations. This approach is usually called optimization with low instability in frequency. Instability can be different - 2.5%, 5%, 10%. In this case, the partial frequency of the damper varies approximately in the same range (0.96 - 0.995). Figure 2 shows the dependence of the damping coefficient on the relative mass of a damper. As seen from the graph, for small values of b, between K_e and ϑ_1 there is an almost linear dependence.

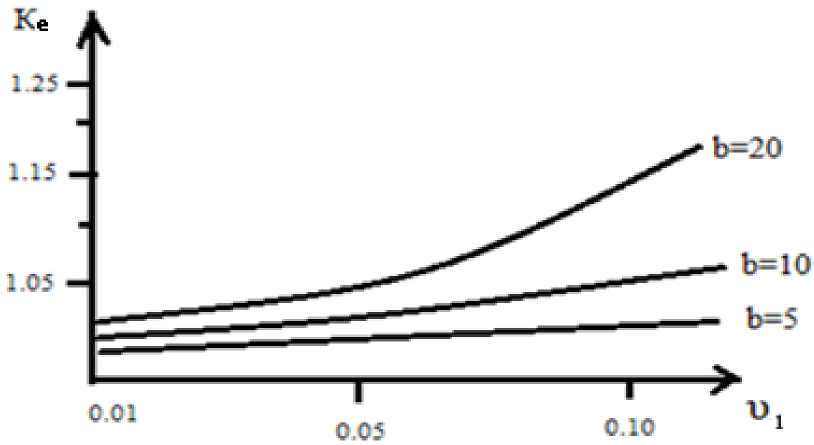

Figure 2. Damping coefficient versus damper mass

From the optimization results it follows that for the systems where there is high energy dissipation, the partial frequency should be 15-25% lower than the frequency of the structure, and the attenuation in the damper should be quite high - 0.1 - 0.2. At ± 5% instability, the damping effect reaches 25%.
It was stated that even at small instability in frequency and small b, the damping coefficient is small, and in soils of less density (b=20), the use of dampers gives a good effect. As noted in [2], the use of a two-mass damper allows expanding the range of effective vibration damping.
When using a two-mass damper, the main damper is m_1, connected by elastic links to the protected system. An additional (constructional) damper m_2, having a sufficiently small mass, is connected consecutively with the main damper.
The damped frequency range is greater for the case of a two-mass damper ($\vartheta_2 \neq 0$) (Figure 4) than for a single-mass damper (ϑ_2 =0) (Figure 3). With increasing ϑ_2 the damping effect increases. The coefficient K_e increases to ϑ_2 =0.05, and at $\vartheta_2 > 0.05$ the coefficient of efficiency K_e begins to decrease.

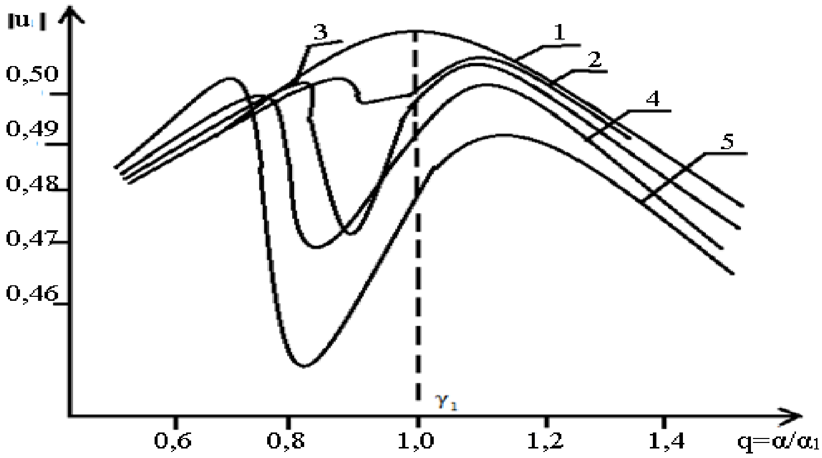

Figure 3. FRC for a disk with a damper. b = 10; 1- ϑ_1=0, 2- ϑ_1=0.01, 3 -ϑ_1=0.03, 4 - ϑ_1=0.05, 5 - ϑ_1=0.10

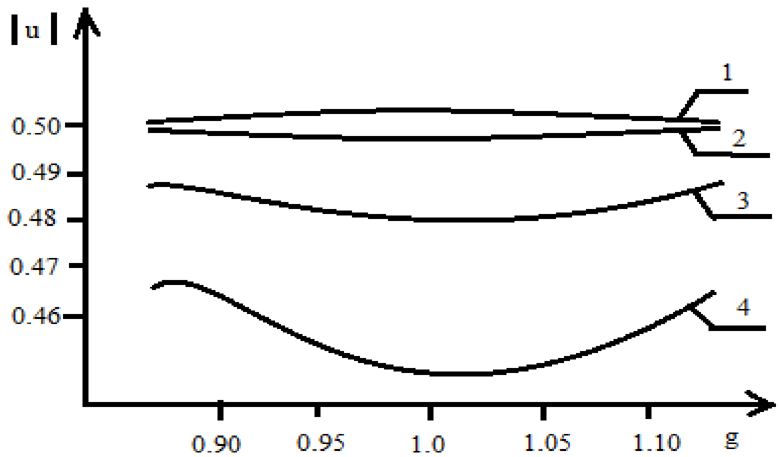

Figure 4. FRC for a disk with a damper. b = 10, ϑ_2=0.05; 1- ϑ_1=0, 2- ϑ_1=0.01, 3 -ϑ_1=0.05, 4 - ϑ_1=0.10

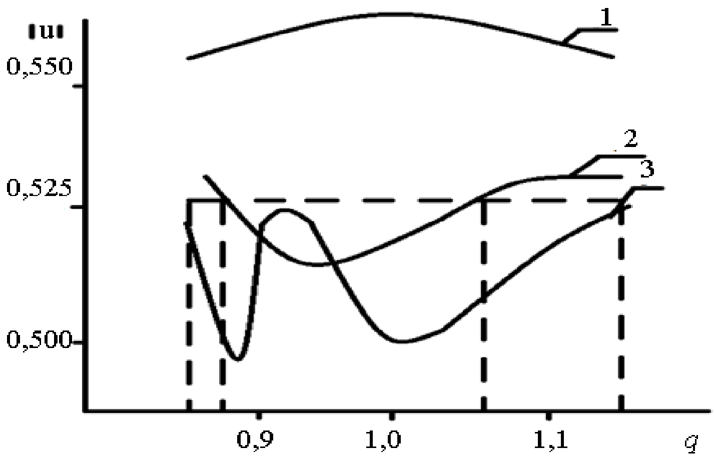

Figure 5. FRC for a disk with a damper. b=20. 1 – ν_1 =0, ν_2=ν_3=0; 2 - ν_1 =0.05, ν_2=ν_3=0; 3 - ν_1 =0.05, ν_2=ν_3=0.01

Present the results of a three-mass damper to suppress the amplitude of disk displacement oscillations. Here, the total mass of the damper system for all compared options is assumed to be the same and $f_{2}=f_3$. The structure of a three-mass damper is formed by attaching two additional masses (m_2 and m_3) to the main damper m_1 (Figure 1b).

Calculations show that the difference in the effects of damping the amplitude of the disk oscillations with three-mass damper and single-mass damper is small. However, the three-mass damper significantly expands the frequency zone of effective damping (Figure 5).

The masses m_2 and m_3 of the dampers work effectively in the entire frequency domain in the case f_2 = 0,95 < f_1 (figure 6). But if it is possible to reduce the frequency interval, then the damper is more efficient when $f_2 > f_1$. In this case, the damping result is improved by 6-15%.

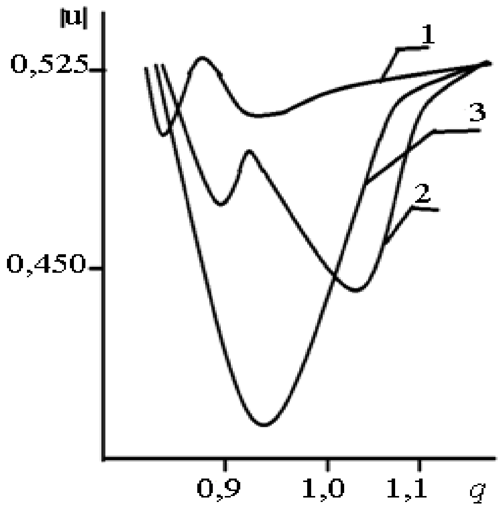

Figure 6. FRC for a disk with a damper. b=20. ν_1 =0.05, $\nu_2 = \nu_3 = 0.01$; f_1=1, $\mu_1 = 0.21$, $\mu_2 = 0.10$; 1- f_2= 0.95; 2 - f_2=1.0; 3 -f_3=1.025

In the case of similar setting of all masses, i.e. when $f_1 = f_2 = f_3$, the whole system works as a single-mass damper. The same conclusion can be drawn when f_1 changes at fixed, $f_{2,}f_3$ (Figure 7).

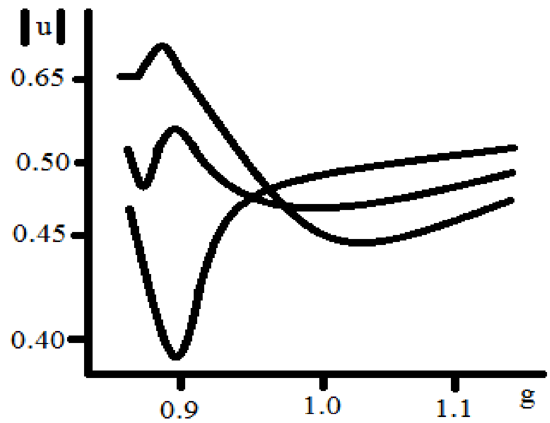

Figure 7. FRC for a disk with a damper. b=20. ν_1 =0.05, $\nu_2=\nu_3=0.01$; f_2=0.95, μ_2 =0.10, μ_1 =0.25; 1- f_1=0.95; 2 - f_1=1.0; 3 -f_1=1.05.

A comparison of the performance of different vibration dampers is presented in Table 2.

Table 2. Comparison of damper systems

Type of damper system	b	ν_1	Parameters of the main damper		Damping effect	
			f_1	μ_1	By the amplitude of displacements	By the width of damped frequencies *, %
Single mass damper	20	0.05	0.984	0.144	1.08	-
Two-mass damper with consecutive mass connection	20	0.05	0.905	0.124	1.13	6
Three-mass damper	20	0.05	1.00	0.24	1,16	40

* Compared to a single-mass damper.

4. Conclusions

Calculations show that the difference in the effects of damping the amplitude of disk oscillations by three-mass and single-mass absorbers is small. A three-mass absorber significantly expands the frequency zone of effective damping (Figure 5).

Table 2 shows that the three-mass damper almost seven times expands the frequency attenuation zone compared to the two-mass one. Since the influence of the masses m_2 *and* m_3, was studied, their parameters changed in calculations, and for m_1 the quantities ν_1, f_1, μ_1 were taken constant. With increasing mass m_1 the damping effect of the oscillation amplitude improves. Therefore, if it is necessary to reduce the amplitude of disk oscillations, then it is necessary to optimize the mass parameter m_1, and if to expand the range of frequencies of the damper effective operation— it is necessary to optimize the mass parameters m_2 *and* m_3.

The masses m_2 *and* m_3 effectively work in the entire frequency domain in the case $f_2 < f_1$ (Figure 6). But if it is possible to reduce the frequency interval, then the damper is more effective provided $f_2 > f_1$. In this case, the quenching result is improved by 6-15%. In the case of the same setting of all masses, the entire system works as a single-mass absorber.

It should only be noted that the damper will operate effectively in the case with a stable impact frequency close to the eigenfrequency of the disk, which is almost similar for both cases.

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