Magneto-liquid damping method and analysis of generated dissipative characteristics

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Abstract. The paper presents the problem of damping technological equipment oscillations by electrical systems. A method of reducing the emerging vibrations using dampers with a magnetic fluid is proposed. The variants of the optimal location of the permanent magnets and the interaction of their fields for the effective design of the magneto-liquid damper are considered. The optimal scheme is obtained – "for repulsion". The analysis of the known statistical data is carried out, and the correlation dependence of the dynamic viscosity on the magnetic field parameters depending on the gap between the permanent magnets is obtained. The values of vibration energy dissipation for the proposed magnetic- liquid damping method are obtained. The universality and adaptability of this method of damping vibrations in the process of reducing the vibrations of the technological equipment have been proved.

1. Introduction

Vibration and various types of technological equipment oscillations arise as a result of changes in the internal pressure that recur with a certain frequency, or when exposed to external disturbing forces. They are the mechanical oscillations of a certain amplitude and frequency of the technological equipment or its individual elements.

Vibration often causes localized damage in flange joints, welds, etc. If the technological equipment node experiences other impacts, then its complete destruction may occur. These consequences are the cause of the need to reduce vibrations in the technological equipment [1].

The damping process is the reduction of oscillations by introducing additional reactances (impedances) into the system. Reactive resistance increases with the installation of vibration dampers. The most common dynamic absorbers are damping elements containing springs, technical rubbers, etc. Under constant influence of alternating loads, these damping elements wear out and fail. As a result, the violation of the integrity of the damping elements leads to an inefficient process of damping and the operation of the technological equipment [2].

2. Properties of magnetic liquid

Scientists in the field of vibration damping suggest using various kinds of magnetic liquids as a damping element.

The peculiarity of magnetic fluids lies in the combination of high fluidity and magnetization, which is tens of thousands of times greater than that of ordinary liquids, since each nanoparticle is a permanent magnet. Under the action of thermal motion, the particles move randomly, and under the action of a magnetic field, the orientation of the magnetic moments of the particles occurs, and the rheological properties change. This behavior allows for the use of magnetic liquids in applied problems.

The properties of a magnetic liquid are influenced by the concentration of the components it contains and the magnitude of external forces. Thus, the change in the concentration and magnitudes of the acting forces allows one to adjust the properties, both during the manufacture of the magnetic liquid and during operation [3].

Viscosity coefficients are the most important parameters that characterize the dissipative and structural properties of colloidal substances, in particular magnetic liquids. They take into account all the internal friction mechanisms that are characteristic for magnetic liquids, which include the dissipation of energy in a liquid, the friction of a liquid against the surface of magnetic particles.

The study of the dependences of viscosity coefficients on temperature, density, concentration and strength of an external magnetic field allows one to estimate the mechanism of viscous dissipation in the internal friction of magnetic liquids. With increasing of density and concentration, the values of the coefficients of the bulk and shear viscosity of the magnetic fluid increase, and with increasing of the temperature, they decrease. With an increase in the magnetic field gradient, these coefficients increase.

If the concentration and size of the particles of the magnetic material are increased, the stabilization mechanism of such a liquid changes from adsorption-solvation and electrostatic to structural-mechanical and hydrodynamic; stabilization of such systems will occur due to the high concentration of magnetic particles and high viscosity of the entire dispersed system. Such concentrated magnetic liquids are called magnetorheological liquids [4].

3. The method of magnetic-liquid damping

The properties of magnetic liquids are determined by the totality of their components (solid magnetic phase, dispersion medium and stabilizer). Variation of the components allows changing their physicochemical parameters depending on the conditions of their use, which allows for their use in damping devices [3-5].

Magnetic-liquid damping occurs due to internal friction in the liquid; kinetic energy of mechanical movements and vibrations is dissipated. In the production of magnetic liquids, it is easy to adjust their magnetization and viscosity, which, in turn, affect the damping characteristics of the device.

Due to the properties of magnetic liquids such as fluidity, compressibility of a liquid medium and significant magnetization, it is possible to use them in various fields of engineering and technology.

There are designs of magnetic-liquid dampers that imply a change in the viscosity of the magnetic fluid under the action of the field of an electromagnet, which is turned on at the required amount of vibration, which is fixed by the sensor. These types of structures have a number of drawbacks, such as the complexity of the design, low damping capacity due to the possible delay in sensor readings, high energy costs for the operation of an electromagnet. Therefore, it is necessary to consider the possibility of using permanent magnets in magneto-liquid dampers [6, 7].

Magnetic liquid changes its properties under the action of a magnetic field, both a permanent magnet and an electromagnet. When the magnetic fluid is in the field, the magnetic nanoparticles, which are components of the magnetic liquid, acquire the direction given by the magnetic field lines. Accordingly, when the magnetic liquid is located in the field of two permanent magnets, the magnetic liquid layout can take two options, depending on the magnet design "for attraction" (Figure 1, a) or "for repulsion" (Figure 1, b).

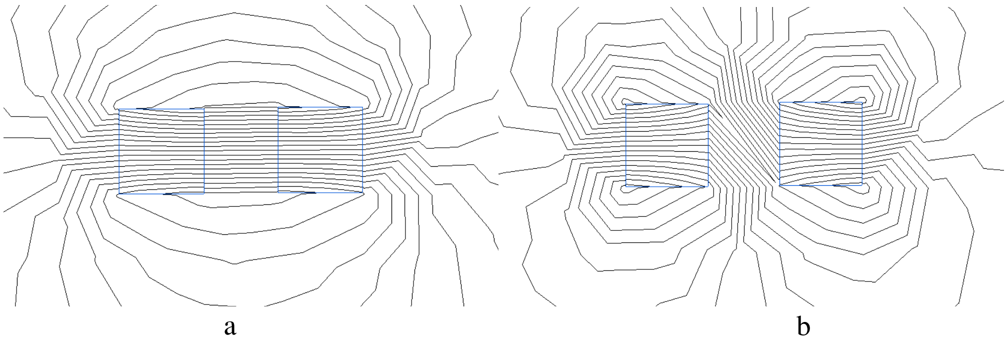

Figure 1. The distribution of magnetic fields at the location of the magnets: a) scheme "for attraction", b) scheme "for repulsion".

A magneto-liquid damper with a magnetic fluid in the field of permanent magnets, according to the "for repulsion" scheme, reduces the longitudinal oscillations of the technological equipment. The arrangement of magnets "for attraction" will not contribute to the interaction of magnetic liquid and oscillating parts of the technological equipment.

The design scheme for reducing the longitudinal oscillations is shown in Figure 2. The damping process is carried out due to the viscous interaction of the piston 1 with the magnetic liquid 4, which is located in the magnetic field of the permanent ring magnets of the repulsion circuit located between the upper and lower bases 5 and 6.

Viscosity of the magnetic liquid depends on the magnitude of the magnetic field, which is regulated by changing the gap *Δ* between the permanent magnets. The change of the gap *Δ* is carried out under the influence of the pressure disk 4 on the upper base 5, which returns to its original position by a magnetically permeable membrane with a gas chamber 6.

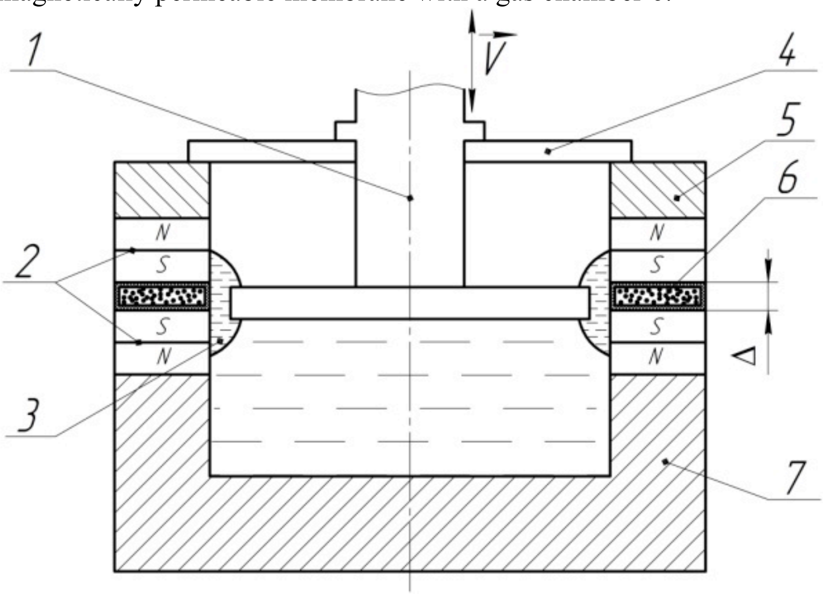

Figure 2. Design scheme for reducing longitudinal vibrations: 1 – piston; 2 – permanent ring magnets; 3 – magnetic liquid; 4 – pressure disc; 5 – upper base; 6 – membrane with a gas chamber; 7 – lower base.

4. Calculation of damping characteristics

Let us consider the scheme of the magnets "for repulsion". The values of repulsive force, magnetic field strength for two permanent magnets and magnetic induction included in the magnetic liquid, depending on the gap *Δ* was found using the student version of the Elcut software package - the axisymmetric problem of magnetostatics was solved [8]. The result of the estimation for the three Brands of permanent magnets is given in Table 1.

Table 1. Estimation of the characteristics of the magnetic-liquid damper in the software package Elcut

Gap Δ, m	Repulsive force F, N		
	N35	YX-24	18БА300
0.001	1508	1200	177
0.004	1141	730	113
0.008	860	487	75
0.011	680	400	60
0.019	440	290	51
0.029	185	158	25
0.038	57	24	14
0.050	40	15	4
	Magnetic field strength H, A/m		
0.001	403380	100040	319010
0.004	363970	75547	270220
0.008	271660	65270	224230
0.011	240140	58294	208750
0.019	210020	47335	172430
0.029	167310	38193	131820
0.038	119680	27886	100690
0.050	67676	14538	50302
	Magnetic particle induction M_s, T		
0.001	484.056	120.048	382.812
0.004	436.764	90.6564	324.264
0.008	325.992	78.324	269.076
0.011	288.168	69.9528	250.500
0.019	252.024	56.802	206.916
0.029	200.772	45.8316	158.184
0.038	143.616	33.4632	120.828
0.050	81.2112	17.4456	60.362

The change in the dynamic viscosity of a magnetic liquid located in the field of two permanent magnets of different Brands of the "for repulsion" scheme is proportional to the repulsive force. The viscosity values are obtained by estimation according to the method proposed by R. Kaiser and G. Miskolczy [9]. The estimations were made taking into account the monodispersity of the magnetic particles in the solvent and the normality of the direction of the magnetic field to the shear plane. The functional relationship of the related parameters is as follows:

$$\eta = f(\eta_0; M_s; d; k; T; H; r; n), \tag{1}$$

where η - the dynamic viscosity of the magnetic liquid; M_s – the magnetic particle induction, d – the diameter of the magnetic particle, k - the Boltzmann constant, T - the solvent temperature, H – the magnetic field strength, r – the shear rate, n – the concentration of magnetic particles.

R. Kaiser and G. Miskolczy presented the distribution of viscosity values from magnetic field values (Figure 3), but no analysis is provided that defines a general law for the dependence of the viscosity of a magnetic liquid on the acting magnetic field [9]. With the correlation of the parameters obtained by R. Kaiser and G. Miskolczy, the dependence was obtained, allowing to determine the value of the dynamic viscosity of the magnetic liquid:

$$\eta = 0.243 \ln(-33.642 \frac{r\eta_0}{M_s H} + 1) + 1.868. \tag{2}$$

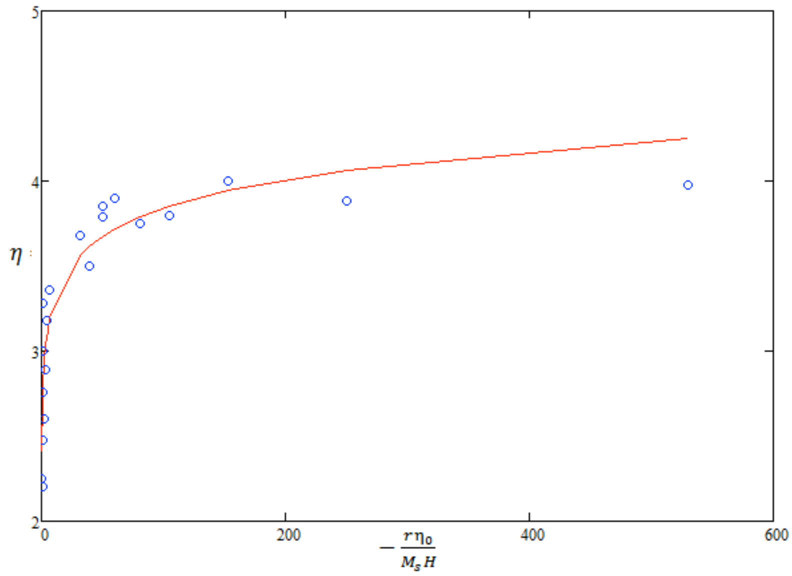

Figure 3. The correlation dependence of the dynamic viscosity of the magnetic liquid (Pa · s) on the parameters of the magnetic field.

The estimation of the dynamic viscosity of the magnetic liquid was carried out in accordance with the values obtained in the Elcut software package, shown in Table 1, and the viscosity values of the solvent η_0=5.61 Pa·s and shear rate r=10^{4}s^{-1}.

In accordance with the estimation made, depending on the brand of the permanent magnet and the gap Δ between them, the magnetic liquid takes on the values of viscosity η given in Table 2.

Table 2. The results of the estimation of vibration damping indicators with a magnetic liquid

Gap Δ, m	N35			18БА300			YX-24		
	η, Pa·s	F_{tr}, N	W_d, J	η, Pa·s	F_{tr}, N	W_d, J	η, Pa·s	F_{tr}, N	W_d, J
0.001	399.04	4357.47	146.38	46.84	511.45	50.15	317.54	3467.48	130.58
0.004	301.92	3297.00	127.33	29.90	326.52	40.07	193.17	2109.39	101.84
0.008	227.57	2485.03	110.54	19.85	216.72	32.64	128.87	1407.22	83.18
0.011	179.94	1964.91	98.30	15.88	173.37	29.20	105.85	1155.83	75.39
0.019	116.43	1271.41	79.07	13.50	147.37	26.92	76.74	837.98	64.19
0.029	48.95	534.57	51.27	6.62	72.24	18.85	41.81	456.55	47.38
0,038	15.08	164.71	28.46	3.71	40.45	14.11	6.35	69.35	18.47
0.050	10.58	115.58	23.84	1.06	11.56	7.54	3.97	43.34	14.60

The viscosity of the magnetic liquid under the action of the field of permanent magnets of three Brands is approximately equal to the value of the dynamic viscosity of technical rubber which is traditionally used in damping devices, which confirms the possibility of using magnetic liquid as a damping element. The advantage is that the replacement of technical rubber with a magnetic liquid allows one to create adaptive systems of damping devices with varying dynamic viscosity depending on the magnitude of vibrations and the corresponding values of the amplitude of oscillations of the technological equipment. Compared to devices with technical rubber, damping devices with magnetic liquid are more reliable, since they are less often repaired and replaced by a working element due to the absence of wear at constant alternating loads.

The efficiency of the damping device is expressed by the attenuation coefficient, the force of viscous friction of the piston in the magnetic liquid and energy dissipation, that is, the loss of energy in one cycle of oscillations of the technological equipment of a certain amplitude. Based on the

Helmholtz model, which predicts an increase in the attenuation coefficient with frequency, the attenuation coefficient is found from equation [10]:

$$\beta = \frac{2}{z}(\frac{\pi\eta\upsilon}{\rho})^{1/2}, \tag{3}$$

where β – the attenuation coefficient; z – the thickness of the layer of magnetic liquid deposited on the wall; η – the dynamic viscosity of the magnetic liquid; υ – the oscillation frequency of the piston; ρ – the density of the magnetic liquid.

The attenuation coefficient for the magnetic liquid was at a thickness of 0.03 m, density 1345 kg / m^3, at a frequency of 20 Hz in the field of permanent magnets of three brands with varying distance. Depending on the distance between the permanent magnets and the viscosity of the magnetic liquid, respectively, the attenuation coefficient takes values in the range from 14.82 to 287.76. The conclusion can be made about the adaptability of damping systems with the inclusion of magnetic liquid as a work element. Based on the law of viscous flow of Newton, the force of viscous friction for a piston moving in a magnetic liquid, in the absence of movement of the inner wall of the damper housing, is determined from the equation:

$$F_{tr} = \eta \frac{vs}{z}, \tag{4}$$

where v – the speed of the piston; s – the area of interaction of the piston with the magnetic liquid.

With an interaction area of 0.021 m^2, piston moving at a maximum speed of 15.6 m/s in a droplet of magnetic liquid with a layer thickness of 0.03 m with varying viscosity depending on the gap between the permanent magnets, the viscous friction force takes on the values given in Table 2.

Excluding the constituent magnetostatics, dissipation from friction on a viscous magnetic liquid, that is, the loss of energy in one cycle of oscillation, is determined from the equation:

$$W_d = \int F_d \mathrm{d}x, \tag{5}$$

where F_d – the damping force.

For viscous damping, equation (5) takes the form:

$$W_d = 2\zeta\pi\beta A^2, \tag{6}$$

where ζ – the degree of damping, with oscillatory motion the received values ζ <1.0; A - piston oscillation amplitude.

For the degree of damping ζ equal to 0.9 (ζ <1.0 for oscillatory motion, ζ>1.0 for non-oscillatory motion, ζ=0 for movement for critical damping - a measure of viscous damping corresponding to the boundary condition between oscillatory and non-oscillatory damping of free motion) [11, 12], we get the value of energy loss in one cycle of oscillation of the piston for dampers with three brands of permanent magnets.

Thus, the energy dissipation takes values given in Table 2 depending on the distance for the magnets brands. It should be noted that the viscosity values and the corresponding dissipations depend on the magnitude of the magnetic field acting on the magnetic liquid, and the composition of the magnetic liquid also plays an important role: the concentration of magnetic particles and the properties of the solvent substance. Thus, it is possible to draw conclusions about the universality and adaptability of the systems of magnetic-liquid dampers to reduce the oscillations of various kinds of technological equipment.

5. Conclusion

Based on the analysis of the interaction of the magnetic fields of permanent magnets, a magnetic-liquid method of damping oscillations of technological devices and equipment is proposed. When evaluating the dissipative properties of the method, a correlation between the viscosity of the magnetic liquid and the parameters of the magnetic field in its dynamics as the gap between the different brands of permanent magnets changed was found.

Based on the known laws of magnetodynamics, an equation for estimating the values of viscous damping of the proposed method is derived. In particular, with a single stroke of the piston, the maximum energy dissipation rate was obtained for neodymium magnets of the Brand N35 and amounted to 146 J (for a cycle 292 J), which proved the effectiveness of the damping method under investigation.

By the properties and the diversity of the composition of the materials of magnets and magnetic fluids, it is possible to ensure the universality and adaptability of the proposed method instead of the classical damping circuits. For example, the composition of the magnetic liquid and the selection of the necessary parameters of the working magnetic field can help to obtain viscosity and energy dissipation, necessary for normal operation of equipment.

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