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Electromagnetic Method for Determining the Internal Resistance of Conductive Materials

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Abstract. The electromagnetic method of vibration diagnostics of rod conductive parts is theoretically described. Natural frequencies of the transverse oscillations of the rod are determined for various boundary conditions. In theory, method of experimental determination of internal friction coefficient of electrically conductive materials is developed.

1. Introduction

It is known that oscillations caused in a solid body fade relatively quickly even in the absence of external resistance. For a long time, this process was not given due importance. Kelvin was the first to notice this phenomenon. A follower of his research was Voigt, who marked the beginning of a microscopic theory. The first review of the problem of internal friction, aimed at clarifying the essence of this phenomenon, was made by K. Ziener [1,2].

Internal friction is understood as the phenomenon of dispersion of energy of elastic oscillations due to internal processes in a solid body, during which mechanical energy of oscillations is converted into thermal energy [1].

With the development of technology, electromechanical systems are everywhere present in our lives. But they are often exposed to vibrations. In their design and manufacture it is important to accurately determine the damping factor, and it primarily depends on the internal friction. Therefore, the experimental determination of the internal friction coefficient is an urgent problem.

There are four hypotheses describing the phenomenon of fading oscillations in an elastic body due to internal friction. The most common is the Voigt hypothesis, according to which the internal friction forces during oscillations are proportional to the speed of movement (viscous friction). The Voigt model has some drawbacks, for example, it is not able to display the relaxation of the material, as compared with the Maxwell and Poiting-Thomson models, which are close to the properties of real bodies [2].

Methods of measurement of internal friction can be divided into the following classes:

- method of free fluctuations;
- resonance method;
- waves propagation method;
- direct determination of stress-strain curves.

Application of the first three classes of methods is possible with some assumptions about the nature of dissipative forces and the linearity of the system. These assumptions are the dissipative force is proportional to the rate of change of deformation (Voigt model) and the type of mechanical behavior does not depend on the deformation amplitude in the stress region used in the experiments. In our case, the measurement of internal friction was carried out using the resonance method.

The electromagnetic method of vibration diagnostics is based on using an external magnetic field. The presence of the magnetic field leads to a distribution of electromagnetic force that acts on the rod. In the case of natural oscillations, the magnetic force is fading, which leads to a change in the attenuation factors of the partial oscillations. Electromagnetic influence possesses selectivity with respect to oscillatory modes, thus, the attenuation factors of various partial oscillations of the rod vary to different degrees. Therefore, it is possible to determine the modes whose factors do not change when the rod vibrates in the magnetic field [3].

The purpose of this study is the theoretical substantiation of the electromagnetic method for determining the internal friction coefficient of conductive materials and its experimental confirmation.

There are several causes of internal friction in materials, and these causes can be recognized by their natural frequency. The task of determining the coefficient of internal friction is important for materials science.

2. Resonant method of determination of internal friction coefficient

An experimental test of the electromagnetic method for determining the internal friction coefficient was carried out on a specially designed installation. A stand is mounted on a massive bed on which an metallic rod 40 cm long and 6 mm in diameter is mounted on a cantilever arm. Aluminum and copper were chosen as the rod material. An external uniform magnetic field is created by two flat magnets, which are fixed so that the induction vector is directed perpendicular to the plane of oscillation of the rod. With the help of a special form waveform generator Tabor WW2571A, a specific current of frequency is passed through the rod. There are forced vibrations of the rod under the action of electromagnetic force. When the frequency of the driving force coincides with any natural frequency of the rod oscillations, a sharp increase in the amplitude of the oscillations occurs - a resonance.

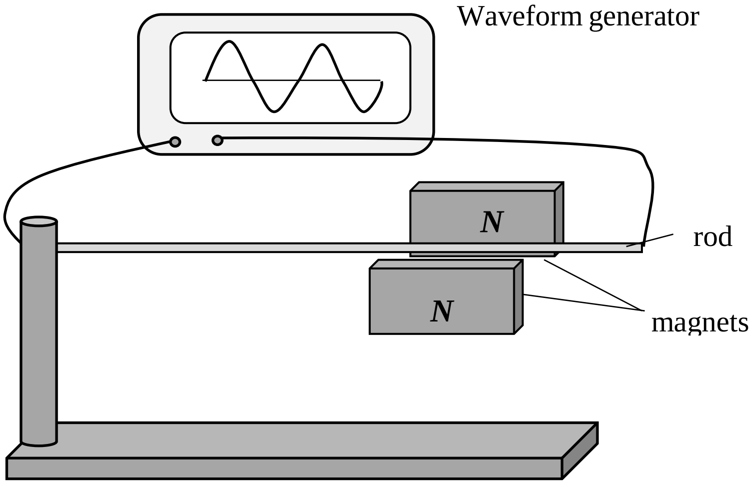


Figure 1. Experimental installation for natural frequencies of fluctuation determination.

In the paper by Tomilin A.K. [3]. The process of transverse oscillations of an electrically conductive rod in an external magnetic field is theoretically described. Based on the data obtained in the monograph [3], we can draw the following conclusions:

- the set of frequencies of an electrical signal depends on the width and location of the active region, on which an external magnetic field acts;
- the electromagnetic effect has a selective property, i.e. a group of natural frequencies of vibrations of the rod, which are not reflected in the electrical signal, is distinguished;
- the magnetic force acting on the rod increases the fading factor of free oscillations, therefore in each particular case it is necessary to compare the magnitude of the mechanical and electromagnetic dissipation.

To determine the internal friction with transverse oscillations of a cantilever rod in a magnetic field using the resonance method, we write the equation of transverse oscillations of a rod in a magnetic field, taking into account the exciting electromagnetic force [3]:

$$EJ\left(\frac{\partial^4 u}{\partial z^4}+\beta^*\frac{\partial^5 u}{\partial z^4\partial t}\right)+m_0\left(\frac{\partial^2 u}{\partial t^2}+\beta\frac{\partial u}{\partial t}\right)+\frac{B^2}{R}\int_{z_1}^{z_2}\frac{\partial u}{\partial t}dz=F_{эм}(t)\ , \tag{1}$$

where: $u(z,t)$ - the dynamic function of displacements, depending on the longitudinal coordinate and time; EJ - flexural rigidity of the rod; β - the coefficient of external damping depending on properties of the environment; β^* - the damping coefficient depending on the properties of the material of the rod; m_0 - linear mass of the rod; R- full resistance of an electrical circuit. The last member in the (1) corresponds to electromagnetic force.

Let's present the function of the driving force in the form:

$$F_{эм}(t)=\sum F_{0i}\sin\omega_i t\,.$$

Let's transform the integral-differential (1) to the system of the ordinary differential (2), using the Fourier procedure and the condition of orthogonality of amplitude functions:

$$\ddot{q}_r+\left(\beta+\beta^* p_r{}^2\right)\dot{q}_r+p_r{}^2 q_r=-\frac{B^2\gamma_r}{\chi_r m_0 R}\sum_{n=0}^{\infty}\dot{q}_n\gamma_n+\frac{j_B AB\gamma_r}{\chi_r m_0},\qquad (r=1,2,...) \tag{2}$$

where: q_r - the generalized coordinate; B - magnetic induction; j_B - current density; A - core cross-sectional area; $\chi_r=\int_{z_1}^{z_2}X^2{}_r dz$; $\gamma_r=\int_{z_1}^{z_2}X_r dz$.

From (2), we determine the damping factor $\tilde{h}_r$ and the damped frequency $\tilde{p}_r$ of the first oscillations, using the formula:

$$\tilde{h}_r=\frac{1}{2}\left(\beta+\beta^* p_r{}^2+\frac{B^2\gamma_r{}^2}{\chi_r m_0 R}\right);\qquad \tilde{p}_r=\sqrt{p_r{}^2-\tilde{h}_r{}^2}. \tag{3}$$

The external resistance (air resistance) and the magnetic dissipation of oscillations have small values compared with the internal friction of the material, therefore, approximately it is possible to accept:

$$\tilde{h}_r=\frac{1}{2}\beta^* p_r{}^2\ . \tag{4}$$

The maximum amplitude of oscillations in the experiment was achieved at the frequency of the electric signal $\omega=23,0\pm0.1s^{-1}$ (for aluminum) and $\omega=14.7\pm0.1s^{-1}$ (for copper). With a further increase in the frequency of the input signal, the amplitude of oscillations of the rod gradually decreased. Accordingly, the cyclic damped frequency has the meaning:

$$\tilde{p}_{alum}\approx144.4s^{-1}\ ;\ \tilde{p}_{copper}\approx92.31s^{-1}.$$

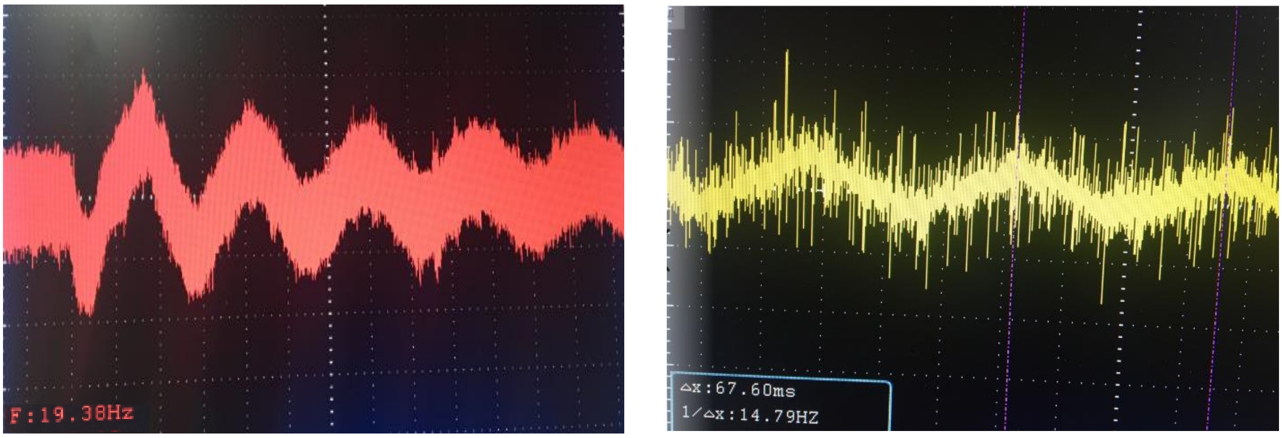
Having determined the experimental cyclic frequency $\tilde{p}$, through (3) we can find the coefficient of internal friction β^*:

$$\beta^*=2\frac{\sqrt{p_r{}^2-\tilde{p}_r}}{p_r{}^2} \tag{5}$$

Table 1 shows the calculations of the internal friction coefficient, attenuation factors and damped frequencies during the induction of magnets B = *1 T* and the action of the magnetic field in the area with coordinates $z_1=0.7l,\quad z_2=0.85l$. The network impedance is 10^6 Ω.

Table 1. The experimental data

Number of oscillations	Material	$p_r\left(s^{-1}\right)$	$\omega\left(s^{-1}\right)$	$\beta^*\left(s^{-1}\right)$	$\tilde{h}_r\left(s^{-1}\right)$
r=1	Aluminum	167.51	144.4	0.0061	84.89
r=1	Copper	115.87	92.31	0.0104	70.04



a) Aluminum b) Copper

Figure 2. Forced oscillation frequency.

Figure 2 shows the graph and the value of the forced oscillation frequency of the rod used to verify the correct determination of the natural vibration frequency by the resonance method. Comparing the oscillograms for aluminium (figure 2a) and copper (figure 2b), it is possible to replace that the value of damping decrement and damping factor of aluminium exceeds the value of damping decrement and damping factor of copper, which is confirmed by calculations and shown in Table 1.

3. Conclusion

The results obtained in this study show possibilities of the electromagnetic method. It can be used to experimentally determine the natural frequencies of transverse oscillations of a rod-shaped object and determination of coefficient of internal friction of the materials from which they are made.

The advantages of this method are: the absence of damage to the test sample, the non-contact measurement method, the invariability of the mechanical properties of the sample during the test. The advantages include a small amount of magnetic dissipation, compared with the impedance of the frequency analyzer. This means that natural frequencies of the electromagnetic method of vibration diagnostics coincide with the frequencies without exposure to a magnetic field.

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