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VISCOELASTIC PROPERTIES OF MAGNETORHEOLOGICAL FLUIDS

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The unique method is used to measure the elastic characteristics of a composite material representing a three-layer vibrating beam consisting of two metal sheets with a layer of a magnetorheological fluid (MRF) between them, which can change its elastic properties under the action of an external magnetic field in real time. The measured characteristics, namely, the dynamic accumulation modulus G_2' *of the damping MRF layer and the loss coefficient* η_2 *both of the damping MRF layer and of the beam as a whole are within the range of values typical for classical viscoelastic bodies, with the results reproduced satisfactorily.*

The problem of control and damping of noise and vibrations is of paramount importance in many branches of industry, including the automobile and shipbuilding industries, robotics, different processing branches, foodstuff and pharmaceutical production, aerospace technology, etc. Conventional damping devices employ a number of classical mechanisms such as slip films [1], a viscous fluid [2], various rubber coatings [3], and composite polymers. However, the majority of the classical damping devices are passive, i.e., designed for particular operating and environment conditions in a narrow range of their parameters. Therefore, the creation of new, unconventional "intelligent" materials and on their basis semiactive adaptive damping devices capable of changing their elasticity characteristics in real time and adjusting to service conditions is a rather urgent problem. Among those are MRFs which can reversibly change their mechanical and elastic properties in the presence of a magnetic field [4]. In this connection, investigation of the viscoelastic characteristics of such systems is of great practical importance.

The present experimental study is based on the standard procedure for measurement of the vibration-damping properties (loss coefficients η, η_2 and dynamic accumulation modulus G_2') of a composite material in the form of a cantilever beam within a frequency range of 50–5000 Hz and at temperatures of $\pm 50^{\circ}$C [5]. This method is used to test materials used in vibration units, acoustic devices, noise absorbing systems: metals, ceramics, rubber, plastics, epoxy matrices, foodstuff, pharmaceutical mass, and so on.

The means of determination of a viscoelastic damping layer located between two metal sheets predetermines the shear strain in the layer provided the following conditions are fulfilled:

a) all measurements of damping characteristics are made in the linear region, i.e., the behavior of a damping material must be described by linear equations of viscoelasticity theory;

b) the amplitude of the stimulating force is independent of frequency;

c) the thickness of the damping layer must exceed that of the metal beam by a factor of not more than four.

The results of calibration experiments with a stroboscopic tube and a microscope have confirmed the "clamped-free" mode of beam vibrations in our experiments (one of the beam ends is fixed) in a wide range of frequencies and amplitudes, which has ensured fulfillment of the conditions.

For the beam geometry with the damping fluid layer between two rigid plates and one of its ends fixed, the design formulas for the main dynamic characteristics are as follows:

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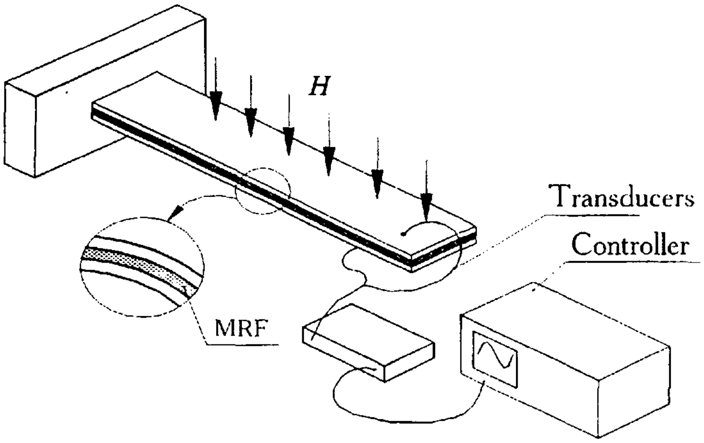

Fig. 1. Diagram of beam sandwich.

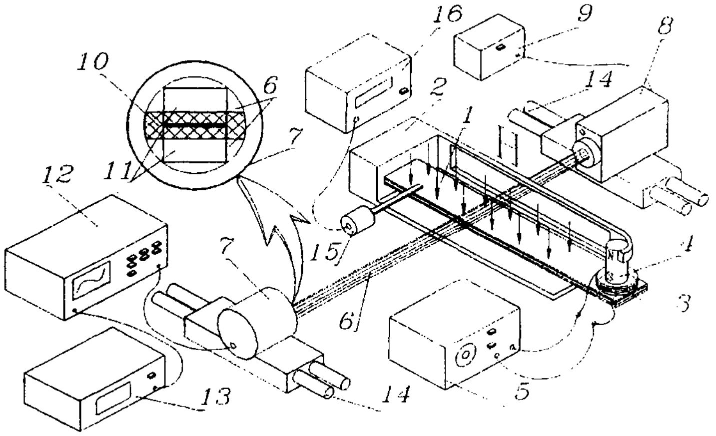

Fig. 2. Diagram of experimental setup used for measuring dynamic MRF properties.

$$G_2' = \frac{A - K - 2(A - K)^2 - 2(A\eta)^2}{(1 - 2A + 2K)^2 + 4(A\eta)^2} \, \frac{2\pi C_n E h_1 h_2}{l^2}, \tag{1}$$

$$\eta_2 = \frac{A\eta}{A - K - 2(A - K)^2 - 2(A\eta)^2}. \tag{2}$$

The adaptive structure is a three-layer beam with the damping MRF layer between two nonmagnetic (aluminum) plates, with one of the beam ends fixed, the dynamic properties of which are investigated in the present work (Fig. 1). Henceforth this construction will be spoken of as a sandwich. As has been mentioned earlier, the feature of the present study is the use of a MRF as a damping layer and control of its damping properties by a magnetic field. Therefore, in addition to meeting the conditions of the procedure mentioned above it was necessary

a) to eliminate the influence of the magnetic field on the signals sent and received by the sensor sandwich;

b) to prevent MRF "outflow" from the sandwich gap without a magnetic field applied to the MRF, when the latter behaves as an ordinary viscous fluid, and to prevent its ejection from the sandwich upon switching on a magnetic field when it behaves as a pseudosolid body.

The first problem was settled by means of an induction coil mounted on the free end of the sandwich and interacting with the permanent magnets located beneath and above it. The second problem was overcome by means of the sandwich construction: the two aluminum plates of the sandwich were dovetailed, which reliably held the MRF in the sandwich and at the same time allowed the plates to slip relative to each other.

A complete diagram of the experimental setup for investigation of the viscoelastic properties of such systems is shown in Fig. 2.

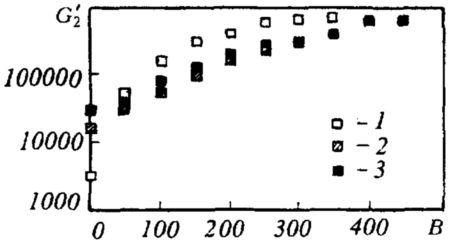

Fig. 3. Accumulation modulus of the damping layer as a function of the magnetic-field intensity: 1) MRF-63; 2) MRF-64; 3) MRF-65.

The gap between the two aluminum plates was filled by the investigated MRF, forming a sandwich 1, fastened by its end to base 2. The sandwich was subjected to action of a voice coil 3 glued to the free end of the sandwich between two permanent magnets 4. The mode and intensity of the sandwich vibrations were regulated by a signal of the prescribed frequency sent to coil 3 from a signal generator 5. The recorder problem was solved with the aid of a contactless optical circuit, namely, the amplitude of sandwich vibrations was controlled by a laser beam 6 and a photoarray 7. In such a circuit, the shadow of the tilting sandwich 10 was projected directly onto adjacent sections 11 of the photoarray, the signal from which entered a differential oscillograph 12, and the resultant signal was recorded by a voltmeter 13. A traverse unit 14 allowed the recording of vibration amplitude along the entire sandwich.

To determine the influence of a magnetic field on the mechanical behavior of the sandwich, the latter was placed in the working space of the electromagnet, and the induction of its magnetic field was recorded by a teslameter 15 with the aid of a Hall generator 16.

In the experiments the main parameters measured were the resonance frequency of forced sandwich vibrations on the second mode f_{res} in the absence of a magnetic field ($B = 0$), when the MRF behaved as a purely viscous fluid, and the shift of f_{res} due to the action of the magnetic field ($B = 0-400$ mT) on the sandwich when the MRF began to behave as a viscoelastic body. Then using formulas (1) and (2) we calculated the main dynamic characteristics, i.e., the accumulation modulus G_2', the loss coefficient η_2 of the damping MRF layer, and the loss coefficient of the sandwich as a whole η.

In order to confirm the validity of this procedure for such fluids, we measured the dynamic characteristics of several samples (MRF-63, MRF-64, and MRF-65) with the same percentage of the coomponents (80 wt.%) but different sizes of carbonyl iron particles:

Sample	Grade of the main component
MRF-63	S-1000, 13 μm in diameter
MRF-64	S-3700, 3 μm in diameter
MRF-65	S-3500, 2 μm in diameter

The accumulation modulus for these fluids G_2' as a function of the magnetic-field intensity is shown in Fig. 3. The composition of MRF-63 the largest particles of carbonyl iron (13 μm) possesses the lowest elasticity in the absence of a magnetic field and manifests the maximum elasticity in relation to the other compositions in a magnetic field, with all other equal conditions being equal. In other words, the elastic properties of the MRF investigated substantially depend on the size of the magnetic particles of the disperse phase.

The same can be said about the loss coefficient η_2 of the damping MRF layer. An analysis of Fig. 4a shows that, as compared to the MRF-64 and MRF-65 in the absence of a magnetic field, when all the MRFs behave as purely viscous fluids, the MRF-63 is the most viscous fluid (the highest h_2). However, owing to the magnetic field, when MRFs begin to manifest the properties of viscoelastic bodies, the MRF-63 is the most elastic fluid (the lowest η_2). This result is also confirmed by tests of the effective viscosity and yield strength of these samples as a function of the magnetic field.

The typical behavior of the loss coefficient h for the sandwich as a whole is shown in Fig. 4b: up to a certain moment η grows with the magnetic-field intensity, thus indicating predominance of the mechanism of viscous damping in the system. When the magnetic-field intensity is above ~200 mT, there is a tendency toward a decrease

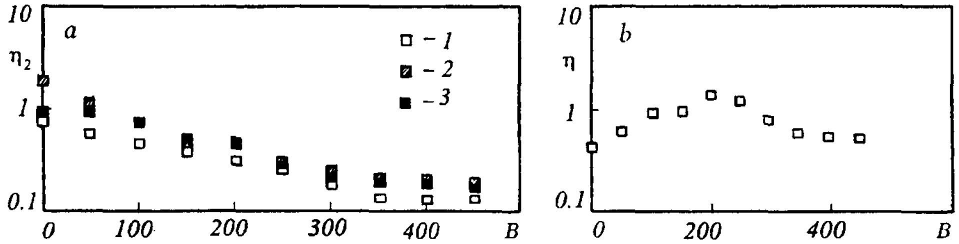

Fig. 4. Loss coefficients of the damping fluid layer (a) and the entire sandwich filled with MRF-63 (b) as a function of the magnetic-field intensity ((1-3) are the same as in Fig. 3).

in η, which is confirmed by the formation of a strong structure of magnetic particles of carbonyl iron in the MRF damping layer and, as a consequence, the predominance of the elasticity properties of the system as a whole.

As is seen, the method of a vibrating beam sandwich fixed at one end with an MRF layer as an intervening damping layer allows the main dynamic characteristics of the MRF itself and of the sandwich as a whole to be obtained in a wide range of determining variables.

An analysis of the numerical values of G_2', η_2, and η obtained has shown that they are within the limits characteristic of conventional viscoelastic bodies with good reproducibility of all the quantities measured.

The present method makes it possible to solve numerous urgent problems on creation of unconventional semiactive damping devices and mechanisms based on "intelligent fluids," among which MRFs are.

NOTATION

G_2', accumulation modulus of the damping fluid layer, Pa; E, Young's modulus of the metal beam; f_n, resonance frequency of the n-th mode of the composite beam, Hz; Δf_n, halfwidth of the resonance of the n-th mode of the composite beam, Hz; $\eta = \Delta f_n / f_n$, loss factor (coefficient) of the sandwich; η_2, shear loss coefficient of the damping material; H, magnetic intensity, kA/m; h_2, thickness of the damping material, m; h_1, thickness of the metal beam, m; $T = h_2/h_1$, ratio of the thicknesses; l, beam length, m; ρ_2, density of the damping material, kg/m^3; ρ_1, density of the metal beam, kg/m^3; $D = \rho_2/\rho_1$, ratio of densities; $A = (f_n/f_{n0})^2(2 + DT)(K/2)$; $K = (1 + T)^{2/6}$; C_n, design coefficient for the n-th mode of the metal beam; $C_1 = 0.55959$, $C_2 = 3.5069$, $C_3 = 9.8194$, $C_n = (\pi/2)(n - 0.5)^2$ for $n > 3$; B, magnetic intensity, mT.

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