

AGING OF PLIABLE COATINGS

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It is shown that the reason for the difference in results of hydrodynamic tests of pliable coatings carried out at different times is the aging of the coatings. It has an effect on the change in the viscoelastic properties of the coating material and accordingly in the vibrational characteristics of the coating itself.

The deposition of pliable coatings is a promising method for decreasing hydrodynamic friction and reducing the generation of noise [1]. Researchers have employed different structures of coatings, whose classification is given in [2], and obtained both positive results (up to 60% of friction reduction [3]) and negative ones (which are also of interest for analysis).

To study the mechanism of the effect of a pliable coating on the characteristics of turbulent flow, it is quite necessary to know the vibrational properties of the coating. A procedure for calculating them from the measured viscoelastic properties of the coating material is proposed in [4]. It is valid for the steady-state regime of deformation. The transient process of the establishment of forced vibrations that is characteristic of the case of turbulent flow is considered in [5, 6].

It is most convenient to analyze the operation of a pliable coating for the simplest structure of the coating – a monolithic homogeneous layer of viscoelastic material with a constant thickness fixed on a rigid base. In the eighties, a series of hydrodynamic tests of these coatings was carried out [7] and a friction reduction of $\approx 18\%$ was obtained. In 1993, a new series of analogous coatings was manufactured and tested [8]. In 1994, these tests were repeated in a cavitation tunnel at the University of Newcastle [9]. A reduction of $\approx 7\%$ in the hydrodynamic friction was reliably shown using different procedures (tensometric measurement of the frictional force, measurement of pressure pulsations by piezoelectric transducers, measurements of the turbulence intensity and velocity profile by a cooling-power anemometer, and measurement of surface-friction pulsations). The present work reveals a possible reason for the spread in results, i.e., aging of the coating, which causes the viscoelastic properties of the material of the coating and accordingly its vibrational characteristics to change.

The viscoelastic properties of materials were measured by the procedure developed in [10, 11]. A specimen of a material in the shape of a plane ring of thickness $H = (2-7)$ mm and radii $R_{\text{out}} = 50$ mm and $R_{\text{inn}} = 40$ mm was cemented to a vibrating table (Fig. 1). The loading mass M was cemented on top of the ring. Using two pickups-accelerometers, we determined the ratio of vibroaccelerations of the upper and lower sides of the specimen Z and the phase shift between them Θ . The dynamic elastic modulus E and the loss factor η were found by solution of the system of equations

$$Z \exp(-i\Theta) = \frac{2E\delta(1+i\eta)}{[M\omega^2/F + E\delta(1+i\eta)] \exp(-\delta H) - [M\omega^2/F - E\delta(1+i\eta)] \exp(\delta H)},$$

$$\delta = \omega \sqrt{\rho/H} \sqrt{(i\eta - 1)/(1 + \eta^2)}.$$

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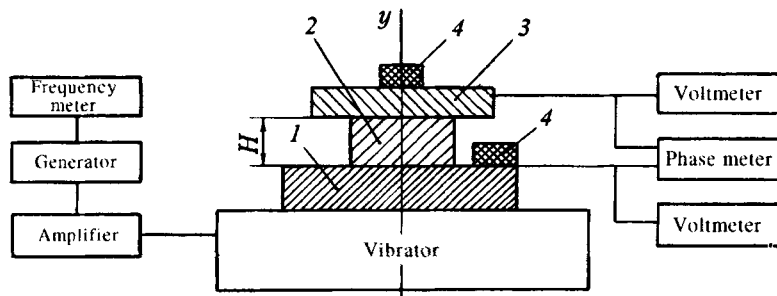


Fig. 1. Diagram of the setup: 1) vibrating table; 2) specimen; 3) loading mass; 4) vibroacceleration pickups.

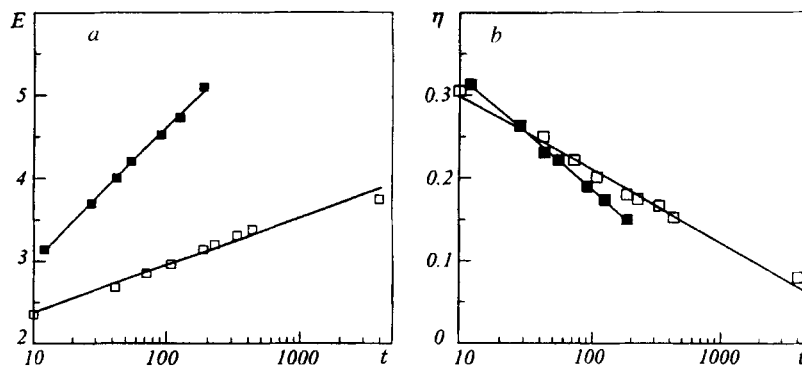


Fig. 2. Aging of viscoelastic properties: a) elastic modulus; b) loss factor (the dark points show material No. 2, the light points, the material of coating A). E , MPa; η , dimensionless; t , days.

Two specimens were tested for aging. The first of them was manufactured of material No. 2 (according to the classification of [7]). The coating made of this material [12] turned out to be the most efficient in the series of tests of 1980. For the second specimen, the same organosilicon compound was used but with a two-fold excess of the content of a catalyst in it (the coating material from [9]). The specimens were aged in a closed room at a temperature of 20°C, away from solar radiation.

Measurement results are presented in Fig. 2. It is seen that with time the elastic modulus increases and the loss factor decreases. This is associated with the cross-linking of macromolecular links, which causes the rigidity of the reticular structure formed to increase and the slippage of the links to decrease [13]. The aging of the properties is approximated well by a logarithmic dependence on time. This means that a coating changes its properties rapidly as soon as it is manufactured, but subsequently the viscoelastic parameters are stabilized as it were. In Fig. 2, the extreme right experimental points correspond to a storage time of 11 years. In this case, we note a small retardation of the aging rate: the value of the elastic modulus turns out to be somewhat smaller than the predicted one, while the value of the loss factor turns out to be larger. The material with the content of the catalyst smaller by a factor of two (No. 2) ages more rapidly, i.e., has a steeper growth in E and a sharper drop in η .

The dynamic elastic modulus and the loss factor depend not only on the deformation frequency but also on the temperature. To convert them to another temperature, use is made of the Williams-Landel-Ferry temperature-time analogy [13]. In accordance with the Williams-Landel-Ferry rule, the dynamic elastic modulus measured for the temperature T_1 at the frequency f_1 is the same as for the temperature T_2 at the frequency f_2 that is determined by the approximate relation

$$\log(f_2/f_1) \approx 900(T_1 - T_2) / [(52 + T_1 - T_g)(52 + T_2 - T_g)],$$

where T_g is the glass transition temperature of the polymer. For the materials used, $T_g \approx 140$ K.

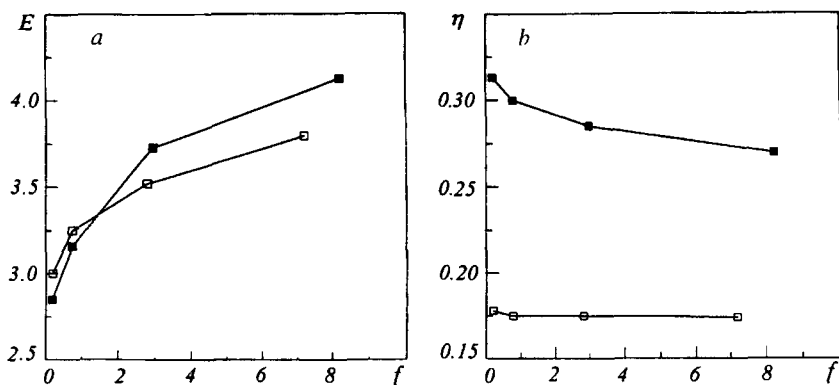


Fig. 3. Viscoelastic properties of coating materials vs. frequency: a) elastic modulus, b) loss factor (the dark points show material No. 2, $T = 20^{\circ}\text{C}$, $t = 10$ days; the light points, the material of coating A, $T = 27^{\circ}\text{C}$, $t = 227$ days). f , kHz.

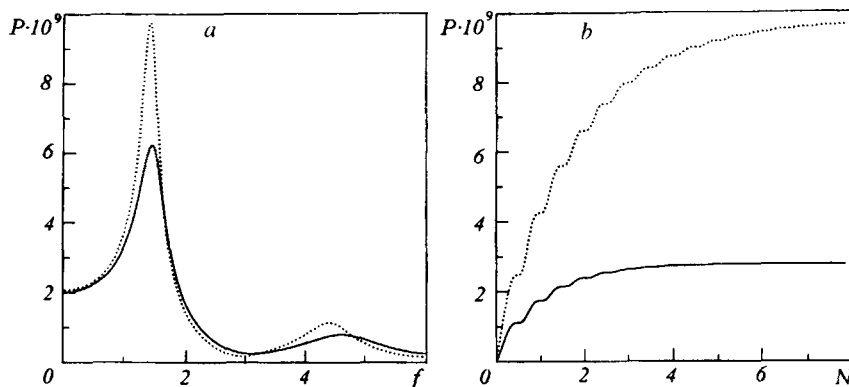


Fig. 4. Vibrational characteristics of coatings: a) frequency dependence of the pliability for a steady-state deformation regime; b) transient process of the establishment of forced vibrations (the solid curves show the coating of material No. 2, the dashed curves, coating A). P , m/Pa.

Figure 3 shows the dynamic viscoelastic characteristics of the materials of coatings that are determined for a specific temperature of the hydrodynamic tests. To extend the frequency range of measurement of viscoelastic properties, data for this figure were obtained with variation of the temperature from -1°C to $+50^{\circ}\text{C}$ and were subsequently converted to the required temperature according to the Williams-Landel-Ferry rule. Hydrodynamic tests of the coating of material No. 2 were carried out within 10 days of manufacture, while the tests of coating A – only within 227 days. Therefore, the viscoelastic properties of the materials of these coatings are measured on the same terms. Figure 3a shows that the elastic moduli of the specimens tested increase with frequency but differ insignificantly from each other.

The difference of their loss factors turned out to be much more significant (Fig. 3b). At the time of the test, the material of coating A had a frequency-independent loss factor of 0.175. A "fresh" coating of material No. 2 has a much higher loss factor ($\eta \approx 0.31-0.28$), which decreases somewhat as the frequency increases.

From the measured viscoelastic parameters of the materials of the coatings we calculated the pliability of these coatings as a function of the frequency by the procedure of [4, 5]. The pliability P is equal to the ratio of the displacement of the coating surface to the pressure applied. Figure 4a shows that the deformation of the coating has a resonance character; therefore the pliable coating interacts only with a portion of the spectrum of pressure pulsations. For the coating of material No. 2, the resonance frequency is $f_0 = 1430$ Hz, while for coating A, it is $f_0 = 1400$ Hz. The practical agreement of the resonance frequencies of these coatings is attributable to the slight difference of the frequency dependences of their elastic moduli (Fig. 3a). The second pli-

ability resonance ($f_0 \approx 4.4\text{--}4.7$ kHz) has a much smaller amplitude, and its effect on the process analyzed is insignificant.

The magnitude of the resonance peak governed by the loss factor of the coating material is different; the coating with a lower η has more pronounced resonance properties. The band of the frequencies of interaction Δf of a coating with a turbulent flow can be defined as the width of the resonance peak at its half-height. Thus, $\Delta f = 800$ Hz for the coating of material No. 2 and 450 Hz for coating A.

Since a coating operates in a rather narrow frequency band, we specify the values of the viscoelastic parameters of the coating materials for further analysis, namely,

coating A: $f_0 \approx 1400$ Hz, $E = 3.335 \cdot 10^6$ Pa, and $\eta = 0.175$;

coating of material No. 2: $f_0 \approx 1430$ Hz, $E = 3.338 \cdot 10^6$ Pa, and $\eta = 0.295$.

For these parameters, the transient process of the establishment of forced vibrations has been calculated by the procedure of [5]. Furthermore, a material density of $\rho = 2.14 \cdot 10^3$ kg/m² and a coating thickness of $H = 7 \cdot 10^{-3}$ m were taken for the calculation.

Calculation results are presented in Fig. 4b. It is seen that the transient regime of the establishment of forced vibrations in the coating of material No. 2 is half as short as in coating A. Hence, the first coating reacts more accurately (with a smaller time delay) to a change in the amplitude of the harmonics of pressure pulsations that correspond to the first resonance peak of pliability of the coating (Fig. 4a).

Furthermore, the high resonance properties of coating A mean that the vibrations which have already developed will attenuate approximately twice as slowly as for the coating made of material No. 2. In this case, deformation waves that propagate from each point of the local deformation of the coating do not attenuate rapidly enough and are efficient in a radius of several wavelengths. This violation of the unambiguous agreement between the applied field of pulsating pressure and the deformation pattern of the surface can cause the efficiency of a friction reduction to decrease.

NOTATION

H , thickness of the coating or the specimen; R_{out} and R_{inn} , outer and inner radii of the specimen; M , loading mass; Z , ratio of vibroaccelerations; Θ , phase shift; E , elastic modulus; η , loss factor; ρ , density of material; ω , cyclic frequency; F , cross-sectional area of the specimen; f_1 and f_2 , deformation frequencies; T_1 and T_2 , test temperatures of the specimen; T_g , glass transition temperature; t , time; f_0 , resonance frequency; Δf , interaction-frequency band; P , pliability; N , number of periods of vibrations.

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