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COMPARISON OF CALCULATION AND MEASUREMENT DATA ON VIBRATIONAL CHARACTERISTICS OF PLIABLE COATINGS

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The experimentally measured complex pliability of a viscoelastic coating is compared with the theoretical calculation carried out on the basis of the measured dynamic elastic modulus and the loss factors of the coating material. The coating thickness was chosen so that the frequency ranges of determination of the viscoelastic properties and of the complex pliability coincide.

The first cause of the action of pliable coatings on the near-wall turbulence is the deformation of coatings under the action of pressure pulsations. Therefore, it is absolutely necessary to know the response of the coating to the applied field of dynamic stresses, and the problem of decreasing friction by pliable coatings in the first approximation is split into two separate problems (Fig. 1), as is done in [1–4].

The wall deformation fields can be determined experimentally [5–8]. However, this straightforward procedure is exceptionally awkward and tedious not only because of the equipment used, but also because of the large volume of information required to describe random variables (frequency spectra, spatial and time correlations, etc.), and it has not yet led to significant results.

Another way is the calculation of deformations [9]. To this end, it is necessary to know both all parameters of the active start (pressure pulsations) and the vibrational properties of the coating itself. All currently existing theories assume a linear dependence of the degree of deformation on the applied pulsation pressure. The proportionality coefficient is called the pliability of a coating (the inverse quantity is rigidity). The second important parameter is the phase angle by which the deformation lags behind the pressure. In [4], four procedures for calculating the complex pliability of various structures of the coating are proposed. To determine the characteristics of the elementary scheme of a monolithic coating (Fig. 1, upper part), it is necessary to know the coating thickness and the viscoelastic properties of the material: the complex elastic modulus and the Poisson ratio. The real part of the elastic modulus is called the elastic modulus $E(\omega)$ and the ratio of its imaginary part to the real one — the loss factor $\eta(\omega)$. In [10], the specific requirements on the measurement of the viscoelastic properties of pliable coatings and a plant complying with these requirements are described.

In [11, 12], a method for measuring the complex pliability is proposed. Below, a comparison of the measurement data on the complex pliability of a monolithic coating with the theoretical calculation by the method of [2] is given. As the object of measurement, SKTN-1(A) polydimethylsiloxane vulcanizate [13], having the structural formula $[–Si(CH_3)_2–O–]_n$, was chosen. This material is widely used to prepare coatings [14, 15] due to the fact that it is polymerized at room temperature and atmospheric pressure by adding a catalyzer. The lifetime of the mixture is several hours, which readily permits making specimens of various forms. Figure 2 shows the viscoelastic properties of this material measured by the methods of [10, 16]. It is seen that during storage the elastic modulus increases and the loss factor decreases. The frequency band of determination of the viscoelastic properties decreases from 250–300 Hz (four days after the coating was made) to 370–390 Hz three months after.

Simultaneously two specimens were prepared: (1) a flat ring (d_{ext} = 50 mm, d_{int} = 40 mm, thickness = 5 mm) for measuring the viscoelastic properties; and (2) a disk (D = 200 mm; H = 20 mm) for direct measurement of the complex pliability.

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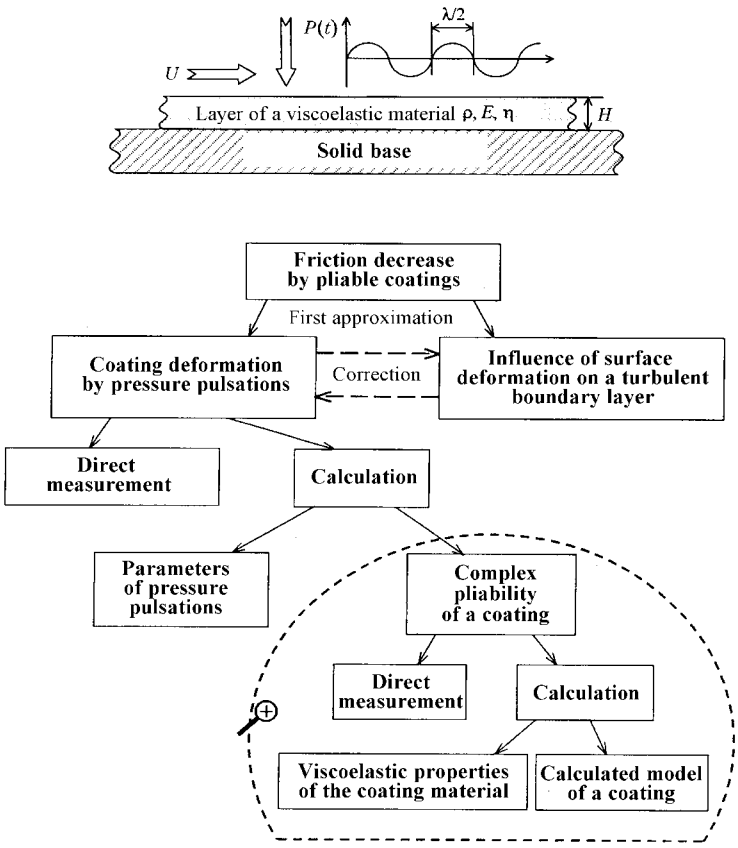

Fig. 1. Directions of studying the mechanism of friction decrease by pliable coatings.

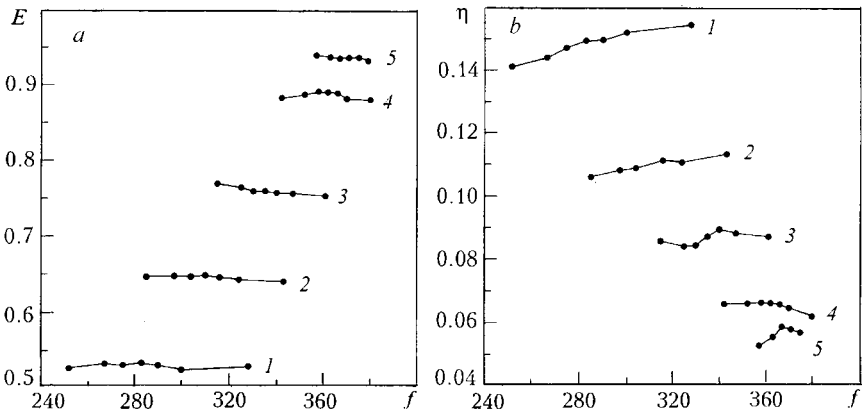

Fig. 2. Elastic modulus (a) and loss factor (b) of SKTN-1(A) vulcanizate depending on the storage time: 1) 4; 2) 11; 3) 25; 4) 57; 5) 95 days. *E*, MPa; *f*, sec^{-1}.

From preliminary measurements [12], the disk thickness was chosen so that its resonance frequency was in the range of determination of viscoelastic properties. This made it possible to manage without the Williams–Landel–Ferry temperature-frequency analogy [17].

To make measurements at such low frequencies, we had to take a number of measures to suppress noise at 50 and 100 Hz. To this end, we used the Butterworth filter to cut-off frequencies below 200 Hz and a thorough screening of the signal circuits. Moreover, the tube of the first amplifier stage of a VÉDS-100 B vibration-testing machine was heated by direct current, which made it possible to reduce the background noise to a reasonable level.

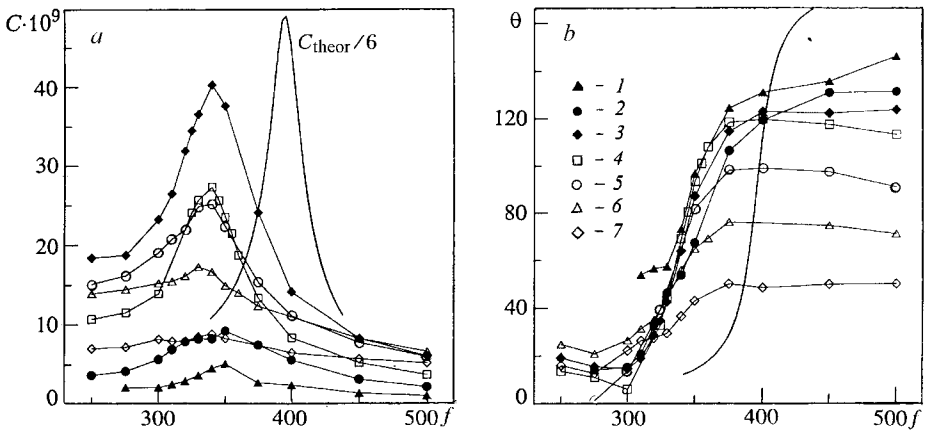

Fig. 3. Dynamic pliability of a coating (a) and phase lag of deformation behind the action (b) at various sensor diameters (solid lines, calculation by the measured viscoelastic properties): 1) d = 80; 2) 40; 3) 25; 4) 18; 5) 10; 6) 8; 7) 6 mm. C, m/Pa; θ, angular degrees; f, $\sec^{-1}$.

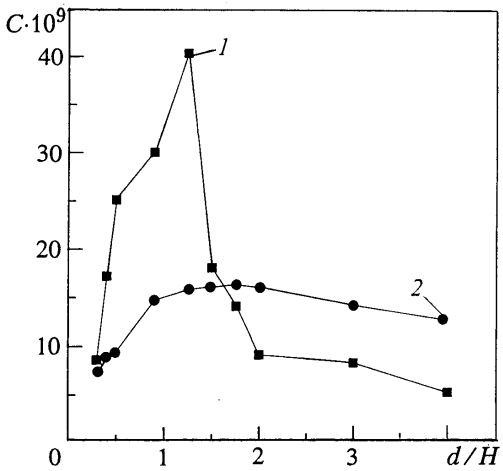

Fig. 4. Comparison of the dynamic pliability (1) with the static one (2). C, m/Pa.

The contact area of the dynamometric sensor with a pliable surface was varied from 0.3 cm^2 (d = 6 mm) to 50 cm^2 (d = 80 mm). To this end, we made a series of new sensors with a diameter of more than 25 mm and calibrated them by the method described in [12].

Figure 3 shows the complex pliability of the coating being investigated measured by sensors of various diameters 95 days after they were made. The pliability maximum (main resonance) is observed at a frequency $f_0 \approx 335$ Hz independent of the sensor diameter (Fig. 3a). The phase shift (shift lagging behind the applied pressure) increases with increasing frequency and sensor diameter (Fig. 3b). Solid lines show the calculation by the measured viscoelastic properties of the material for the same storage time. There was a qualitative agreement in the behavior of the curves; however, certain differences were also revealed: (a) the calculation in [2, 9] yields an overestimated resonance frequency at f_0 = 390 Hz; (b) a strong dependence of the pliability on the sensor diameter was revealed; (c) the pliability value appeared to be much lower than the calculated value; and (d) the phase angle at small diameters is much smaller than the calculated one.

Figure 4 shows a comparison between the dynamic pliability measured at the resonance frequency and the pliability at static deformation determined for various diameters of the contact area. The static pliability maximum is observed when the diameter of the area being pressed is larger than the coating thickness by a factor of 1.5 to 2. The dynamic pliability maximum is found at a smaller value of d/H ($d/H \approx 1.3$). This difference can be explained by the

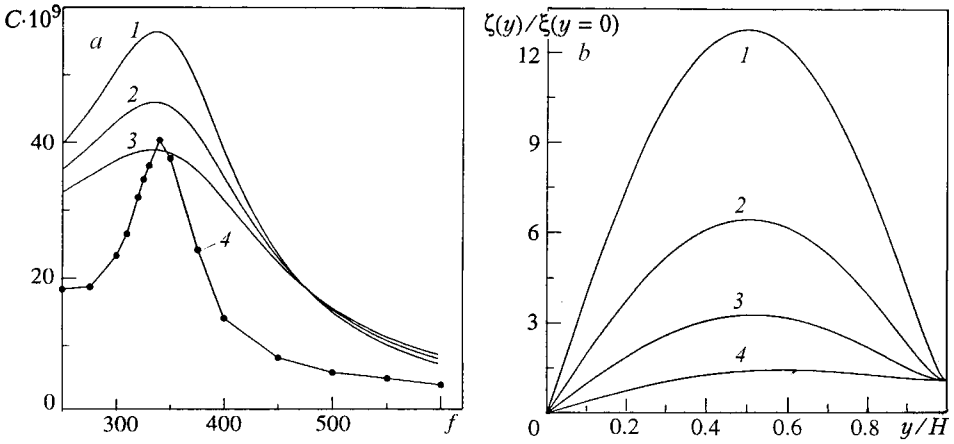

Fig. 5. Correction of viscoelastic properties for making the calculated value of the dynamic pliability agree with the measured value — a [1) η = 0.4; 2) 0.5; 3) 0.6; 4) sensor with d = 25 mm] and change in the value of the deformation in the specimen thickness — b [1) η = 0.05; 2) 0.1; 3) 0.2; 4) 0.5].

display of the coating inertia. At small ($d/H < 0.25$) and large ($d/H > 2$) sensor diameters, the dynamic pliability becomes smaller than the static one. The ratio of the dynamic pliability to the static one is the dynamic coefficient [2, 9]; in this case it is ≈3.5 at the resonance frequency.

As for the operation of a pliable coating in a turbulent flow (Fig. 1, upper part), it may be suggested that the diameter of the sensor contact surface corresponds to half of the wavelength of the pressure turbulent pulsation moving in the direction of the flow at a convective velocity U_c, i.e., $d = \lambda/2$. Naturally, the boundaries of the domain of influence of moving pressure pulsations are not as clear-cut as those of the contact area in measuring the pliability, but nonetheless in the first approximation this can be accepted. A pliable coating will respond to the action of those pressure pulsations (Fig. 3) whose frequencies are close to the resonance frequency of the coating f_0. However, this turns out to be insufficient. As is seen from Fig. 4, the harmonic wavelength of pressure pulsations with frequency f_0 should be of the order of the doubled thickness of the coating. Since $U_c \cong 0.6$–$0.7U$ [18] and $\lambda = U_c/f_0$, the flow rate U at which the coating will actively interact with pressure pulsations is determined by the relation $U = 2f_0H/(0.7–0.8)$. This explains the reason why the value of the increase in the turbulent friction depends on the flow rate [19–21].

Figure 5 illustrates a possible reason for the difference between the experimental and calculated data. Solid lines in Fig. 5a show the calculation of the pliability of a coating of the same thickness and density (H = 20 mm, $\rho = 10^3$ kg/m^3) but with a smaller elastic modulus E = 0.75 MPa and a significantly larger loss factor. A tenfold increase (from 0.055 to 0.55) in η enables one to make experimental pliability values agree with theoretical ones at the resonance frequency, but the extents of their resonance band remain widely differing.

Figure 5b shows how many times the value of the deformation amplitude inside the coating is larger than the deformation amplitude on the coating surface (at $y = H$). It is seen that with decreasing loss factor this ratio rapidly increases. However, since the coating material is practically incompressible, the Poisson coefficient (the ratio of lateral deformations to a given vertical deformation) is 0.5. This leads to a complicated "mound-like" pattern of coating surface deformation, the appearance of significant shear stresses, and the necessity of taking into account the three-dimensional property of the coating in calculating its vibrational characteristics.

The calculation of the viscoelastic properties of materials [10, 16] and coating pliability [2, 9] is based on the solution of the equation

$$\frac{d^2\xi}{dy^2}(1 + i\eta) = -\omega^2 \frac{\rho}{E}\xi,$$

where $\xi(y)$ is the shift of the coating at height y describing the one-dimensional compressive-tensile deformation of the specimen.

In measuring E and η, one uses a specimen of a material in the form of a tablet with a diameter-to-height ratio of ~1 or a flat ring with $(d_{ext} - d_{int})/2H \approx 1$. In this case, the barrel-shaped character of the specimen is taken into account by the shape factor. In [22], for a static deformation, the variational problem of finding a shape of the specimen at which its total energy is minimum has been solved and the dependence of the shape factor on the Poisson coefficient has been defined. In [23], the shape factor at a dynamic deformation of a cylindrical specimen has been determined empirically.

However, the correction of E and η in calculating the vibrational characteristics of the coating did not lead to success (as shown in Fig. 5a); therefore, in their calculation, one should use more complicated equations that take into account the three-dimensional property of the coating.

NOTATION

E, elastic modulus, Pa; η, loss factor; p, material density; ω, cyclic frequency; d_{ext} and d_{int}, external and internal diameters of a specimen for measuring viscoelastic properties; D and H, diameter and thickness of a specimen for direct measurement of the pliability; d, sensor diameter; f_0, resonance frequency of a coating; U, flow rate; U_c, convective rate; λ, wavelength; y, vertical coordinate. Subscripts: ext, external; int, internal; c, convective.

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