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# PROPAGATION OF DEFORMATION WAVES IN A COMPLIANT COATING

**V. M. Kulik**

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*A unit for measurement of the amplitude and length of a deformation wave propagating along a layer of a viscoelastic material glued to a rigid base has been developed and manufactured. It has been shown that at the first-resonance frequency of the coating, the wavelength is equal to a quadruple coating thickness. The variance of the phase velocity of propagation of vibrations has been found. The damping of the vibrations has turned out to be much higher than that in free space. The conditions under which the response of the coating to turbulent pressure pulsations is maximum have been given.*

An explanation for the mechanism of reduction of friction by a compliant coating in turbulent flow by a change in the Reynolds stresses in the near-wall region has been proposed by B. N. Semenov in [1, 2]. Based on this idea, he has developed an algorithm of selection of the parameters of the coating. The results of testing the coatings calculated according to this procedure have shown a reduction in the friction and pressure pulsations [3–5].

To analyze the results of hydrodynamic tests of compliant coatings it is necessary to know their dynamic compliance. The method of its measurement has been proposed in [6], and the results of measurements with the use of vibrating contact areas of different diameter have been given in [7]. It has been found that the dependence of the compliance on the deformation frequency has the form of a resonance peak, and the dependence of the compliance on the vibrator diameter has an analogous shape. These features have been explained in the subsequent work [8]. The independence of the resonant frequency of the coating from the diameter of the vibrator is due to the fact that a standing-wave node is universally present on the rigid surface to which the coating is glued and an antinode is present on the exterior surface. The velocity of propagation of disturbances across the coating is determined just by the elastic modulus and the density of the coating material and is independent of the diameter of the vibrator.

To explain the resulting dependence of the dynamic compliance on the diameter of the contact area it has been assumed that the velocities of propagation of disturbances along the coating and across it are equal. This has suggested that the velocity of turbulent flow is related to the parameters of the coating, i.e., the convective wavelength of pressure pulsations at the resonant frequency is equal to a quadruple thickness of the coating.

In the present work, we experimentally check the assumption on the equality of the velocities of propagation of disturbances along the coating and across it in the range of frequencies similar to the resonant frequency of the coating.

A diagram of the setup in given in Fig. 1. A GMK-1 mechanical-vibration generator and an IZA-2 optical movement meter (Leningrad Optico-Mechanical Plant) are mounted on a massive plate lying on vibration-insulation spacers. A layer of a viscoelastic material is applied into a ring of diameter 590 mm manufactured from a 10-mm-thick steel wire and fastened to a $600 \times 600$ mm$^2$ plate. The size of the contact area of the vibration exciter 1 can vary over wide limits. In this work, we have employed contact areas with a diameter of 5, 10, 13, and 20 mm. The vibrator is smoothly brought into contact with the coating with the use of a mover.

The vibration transducer 2 is manufactured on the basis of a piezoceramic tube from TsTS-19 and is fastened, together with a preamplifier, on a rod moving in parallel to the coating surface. We measure the amplitude of the signal and its phase lag behind the signal from the search coil of the vibrator.

The coating is manufactured from SKTN-1A [9] silicone rubber. The frequency dependences of the elastic modulus and the mechanical-loss coefficient for different storage lives of the material have been given in [7]. The viscoelastic properties have been measured according to the procedure of [10, 11]. For the period between the manufac-

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S. S. Kutateladze Institute of Thermal Physics, Siberian Branch of the Russian Academy of Sciences, 1 Akad. Lavrent'ev Ave., Novosibirsk, 630090, Russia; email: Kulik@itp.nsc.ru. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 77, No. 4, pp. 71–75, July–August, 2004. Original article submitted September 29, 2003.

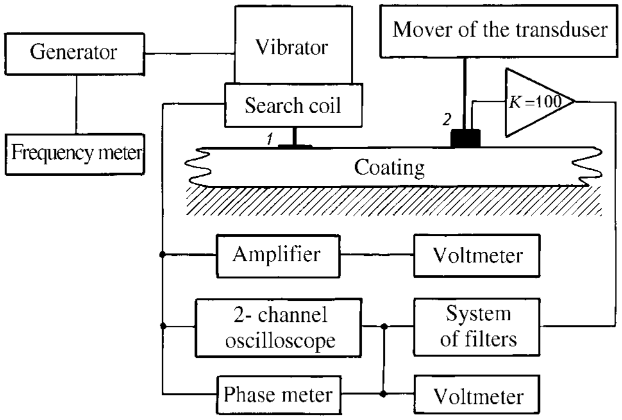

Fig. 1. Diagram of the setup: 1) contact area of the vibrator; 2) vibration transducer.

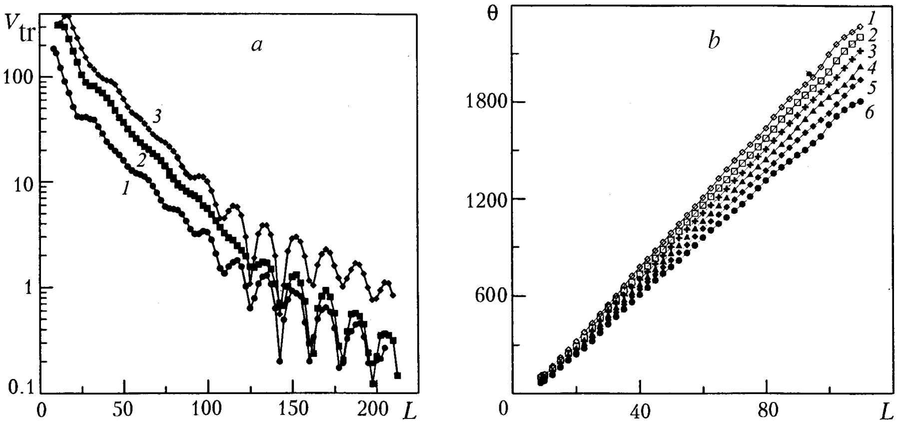

Fig. 2. Amplitude of the signal (a) [$f$ = 800 Hz; 1) the diameter of the vibrator's contact area is equal to 5, 2) 10, and 3) 20 mm] and the phase (b) [1) $f$ = 850, 2) 825, 3) 800, 4) 775, 5) 750 and 6) 725 Hz] vs. distance to the center. $V_{tr}$, mV; θ, angular degrees; $L$, mm.

ture of the coating and its test (approximately 50 days), we have $E \cong 0.9$ MPa and $\eta \cong 0.06$. This corresponds to the resonant frequency of the coating [12, 13]:

$$f_0 = \frac{\sqrt{E/\rho}}{4H}\left[\frac{2\,(1+\eta^2)}{1+\sqrt{1+\eta^2}}\right]^{1/2} \cong 750\text{ Hz}\,. \tag{1}$$

Figure 2 gives the primary experimental data. Figure 2a shows that the signal of the transducer is a result of the combination of two waves — the wave coming from the vibrator at the center of the disk and the wave reflected from the edge. This produces a standing wave against the background of an exponentially damped traveling wave. To the distance $L \approx 10$ cm (one-third of the disk radius), the amplitude of the standing wave is much smaller than the amplitude of the traveling wave, which enables us to quite simply compute the damping factor (see further in Fig. 3c). Figure 2b is a typical example of the phase incursion as a function of the distance to the center. The dependence is linear up to half the disk radius, which enables us to determine the wavelength and the phase velocity of propagation of vibrations. These restrictions in measurements of the amplitude and phase of the signal are related to the sensitivity of the transducer employed and to the signal-to-noise ratio in the amplification path. As is clear from Fig. 2a, the signal of the transducer increases in proportion to the change in the diameter of the vibrating area. The reason is that the vibration amplitude is determined by the mass of the GMK-1 moving part and is virtually independent of the presence

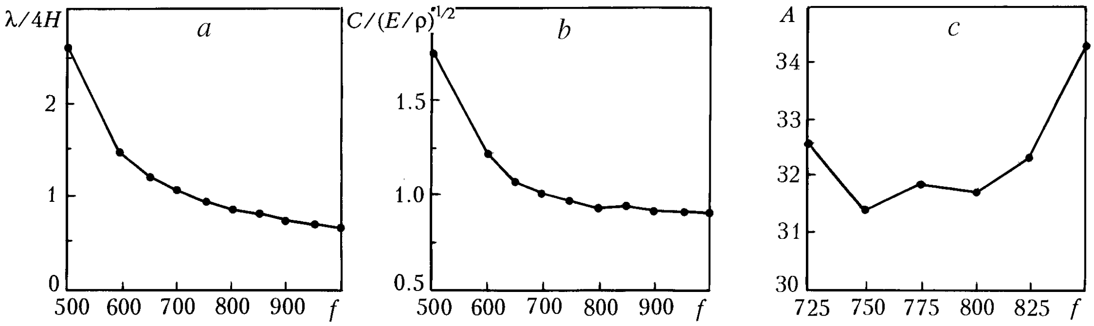

Fig. 3. Dependences of the wavelength (a), the phase velocity (b), and the characteristic length (c).

of contact with the coating. Therefore, the vibration amplitudes on different diameters are equal and the volume of the material forced out from under the vibrator is in proportion to its area and is distributed in the form of a wave on the larger diameter.

Figure 3 shows results of processing of the data obtained. It has been confirmed that at the resonant frequency of the coating, the wavelength of a disturbance propagating along the coating is equal to 4*H* (Fig. 3a). The phase velocity of the wave at the resonant frequency is equal to $\sqrt{E/\rho}$ (Fig. 3b). The observed variance of the velocity is, apparently, attributable to the decrease in the elastic modulus as a function of the frequency [7].

Since the amplitude of the traveling wave decreases because of the "spreading" of its energy with distance from the center and because of dissipation, we have

$$V_{\text{tr}} \sim V^0_{\text{tr}} \exp\left(-L/A\right) L^{-1/2} .$$

In propagation of the wave in free space, we have $A = \lambda/\pi\eta$ [14]. The value of the characteristic attenuation length obtained in the experiment is much lower than the calculated value. This is, apparently, due to the fact that when the wavelength is larger (in this case four times) than the thickness of the layer over which the wave propagates, the influence of the wall on the damping of vibrations becomes very significant. Even for a very small loss coefficient of the material ($\eta \approx 0.06$) the amplitude of the wave decreases *e* times at a distance equal to the wavelength. In [15], B. N. Semenov has introduced the notion of a "locally deformed" coating to describe whose deformation it is unnecessary to consider traveling waves. The calculations carried out by him show that when $\eta = 0.7$ the amplitude decreases 10 times at a distance equal to the wavelength. The data obtained by us show that this estimate is very overstated and the criterion of a locally deformed coating can be extended to a wider range of materials with a loss coefficient much smaller than 0.7.

From the results of the conducted series of experiments [6–8] and the results of this paper, we can draw the following conclusions: for the coating to be able to reduce turbulent friction it must interact with the flow, i.e., the exterior coating surface must be deformed under the action of turbulent pressure pulsations; the larger the amplitude of deflection, the greater the expected effect.

In the investigation carried out, we have determined the conditions under which the response of the coating to turbulent pulsations is maximum.

1. Since the coating possesses inertia, it cannot instantaneously "swing" and follow the change in pressure pulsations. When changes in the pressure pulsations are chaotic, the amplitude of vibrations of the coating surface will be close to zero, i.e., the coating will seem absolutely rigid. The period of coherence of pressure pulsations, necessary to cover the time interval required for establishment of forced vibrations, has been determined in [12, 16]. Thus, when $\eta = 0.2$ it takes three periods of vibrations to swing the coating to the level of 0.7 of the steady-state regime.

2. As early as in [15] it had been shown that the deformation amplitude depends on frequency. The first resonant frequency (found from (1)) of the coating corresponds to a wavelength equal to a quadruple thickness of the coating. A standing wave having a node on the rigid surface and an antinode at the external boundary is formed over the coating thickness. The dependences of the deformation amplitude and the resonance-peak width on the loss coefficient of the coating material have been analyzed in [12].

3. The deformation amplitude depends on the linear dimension of the vibrator. In [8], it has been determined that the interaction will be maximum on condition that the length of the convective pressure-pulsation wave is equal to a quadruple coating thickness, i.e.,

$$U_c = \lambda f_0 = 4Hf_0 \, . \qquad (2)$$

Satisfaction of conditions 1–3 realizes the regime of maximum interaction of the compliant coating with the turbulent flow but speaks nothing of the possibility of reducing friction. These conditions are necessary but insufficient. To obtain sufficient conditions we must turn to the second part of the mechanism of interaction of the compliant wall with the flow, i.e., to the retaliatory process of action of the wall on turbulent flow [17].

One more requirement on a compliant coating had been placed earlier. The deformation amplitude of the coating $\zeta$ must not be too large so as not to violate the condition of hydraulic smoothness $\zeta^+ < 15$. However, deflection of the coating surface by pressure pulsations cannot be compared to the regular roughness, for example, the sand roughness of Nikuradze. For the actual case given in [12, 16] ($E$ = 5 MPa, $\eta$ = 0.2, $H$ = 5 mm, $V_d$ = 0.4 m/sec, and $\rho = 2 \cdot 10^3$ kg/m$^3$), it follows that $\zeta^+ \cong 2$ and the relative deformation of the coating in the flow is $\zeta / H \cong 10^{-3}$; since we have $H = \lambda/4$, $\zeta/\lambda$ will be of the same order of magnitude. Such a smooth deflection (for example, 25 μm at a distance of 2.5 cm) can in no way influence friction. However, this problem must finally be solved by future experiment.

4. In [18], it has been assumed that the resonant frequency of the coating must be equal to the frequency of turbulent ejections. B. N. Semenov [2, 15] has shown the possibility of reducing friction if

$$0.02 < \pi f_0 \nu / V_d^2 < 0.37 \, . \qquad (3)$$

Under this condition, the resonant frequency of the coating is in the phase-frequency region of the predicted positive action. In [5], attention has been given to the fact that the dimensionless frequency of eigenmodes of the coatings employed in the experiments [3–5, 19] is $0.35 < f_0^+ < 0.61$, which correlates with the frequency of turbulent ejections.

Formulas (1)–(3) enable us to calculate the predicted range of thickness of the coating and flow velocities for prescribed $E$ and $\rho$.

## NOTATION

$A$, characteristic attenuation length, mm; $c$, phase velocity, m/sec; $E$, elastic modulus, Pa; $f$, vibration frequency, sec$^{-1}$; $f_0$, first-resonance frequency, sec$^{-1}$; $f_0^+ = f_0 \nu / V_d^2$, dimensionless eigenfrequency of the coating; $H$, coating thickness, mm; $K$, amplification factor; $L$, distance from the center of the disk to the transducer, mm; $U_c$, convective velocity, m/sec; $V_{tr}$, voltage of the transducer's signal, mV; $V_{tr}^0$, initial signal of the transducer, mV; $V_d$, dynamic velocity, m/sec; $\eta$, loss coefficient of the coating material; $\rho$, density of the coating material, kg/m$^3$; $\nu$, kinematic viscosity of the liquid, m$^2$/sec; $\lambda$, wavelength, mm; $\theta$, phase incursion, angular degrees; $\zeta$, displacement of the coating surface, m; $\zeta^+ = \zeta V_d / \nu$, dimensionless displacement. Subscripts: d, dynamic; c, convective; tr, transducer.

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