773. Investigation of dissipative properties of liquid crystalline lubricant layer

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Abstract. This work aims to investigate vibration behavior of rotating roller – a fixed segment friction pair lubricated with pure motor oil and motor oil containing liquid crystal (cholesteryl oleate) additive. Experiments were performed under boundary friction conditions. Mechanical vibrations were registered through the processing and analysis of radial vibration data of the segment, obtained for each lubricant composition under constant roller speed. It is established that vibration level of the segment is reduced at the presence of liquid crystal additive. Theoretical investigations of load-carrying properties of individual layered liquid crystal in a lubricating gap of the film lubrication bearing show a strong increase in load as compared with the equivalent viscous lubricant.

Keywords: liquid crystal, motor oil, friction pair, vibration amplitude.

Introduction

Dissipative properties of lubricants are manifested in both shear and bulk cyclic deformation of the lubricant layer [1]. Under conditions of variable pressures, temperatures and other parameters of state of the lubricant layer there is a rapid redistribution of components of the lubricant, formation and rearrangement of molecular associates and complexes with changes in their mutual solubility. The associates, micelles, and other electrically charged colloidal particles interact with each other and with the surface. This results in changes in the viscosity, electrical conductivity and other properties of the lubricating medium. As the end result, the lubricant dissipates the mechanical energy transmitted to it, transforming the energy into heat, sound and other forms of energy [1].

This process results in the damping effect of the lubricant layer [2], which lowers vibration level in machinery and vehicles and thereby reduces dynamic forces acting on the mechanisms. Furthermore, dissipation is related to viscous resistance forces that influence the load-carrying capacity of the lubricating layer. The dissipative properties of a lubricant are also important in other aspects. Service life of the lubricant can be extended by improving their dissipative properties. Next, dissipative properties influence lubricant capability to reduce the internal energy accumulated during periodic deformations; increase of the density of this energy can lead to breakdown.

It is known that liquid crystals have the fluidity characteristics of a liquid and the elasticity characteristics of a crystalline solid (in the direction perpendicular to the flow), and have a layered structure. Formation of lubricant layers with the mentioned properties on the surfaces of contacting bodies would allow providing simultaneously a high durability, high dissipation properties and a low friction coefficient of friction pairs. This can be achieved by introducing liquid crystals into lubricants, thus realizing the liquid crystal specific “guest-host” effect, i.e. a parallel orientation of lubricant and liquid crystal molecules and formation of liquid crystalline lubricant layer.

Antifriction and anti-wear properties of the liquid crystals are well-studied. These properties appear using liquid crystals as lubricant and as lubricant additives [3-5]. It should be mentioned that the second approach is more promising in terms of economic considerations. It is known that liquid crystals additives to the various lubricants can significantly reduce the friction coefficient of lubricated friction pairs. In isolated cases, when twisted nematic liquid crystals are used as additives, maximum reduction of the friction coefficient of friction pairs is reached 5 times [5], wear of friction surfaces decreases 20 times [5] and friction zone temperature – 2 times [4] in comparison with pure lubricants. It may be expected that liquid crystals also increase dissipative properties of lubricants. However, scientific literature provides no information about dissipative properties of lubricant with liquid crystals.

The present work intends to contribute for improving knowledge on the relationship between vibration phenomena and lubrication in friction pairs. This is done by studying how liquid crystals additives can affect the mechanical vibration of rotating roller – fixed segment friction pair lubricated under boundary lubrication conditions.

Mathematical study

To understand the rheological properties of layered (smectic) crystals the model shown in Fig. 1 was proposed [6]. According to this model layers of liquid crystals are separated by porous walls connected by springs. Newtonian fluid flowing along the layers is not influenced by walls, but in direction normal to the wall fluid experiences a resistance from walls. Resistance value is proportional to the normal pressure gradient.

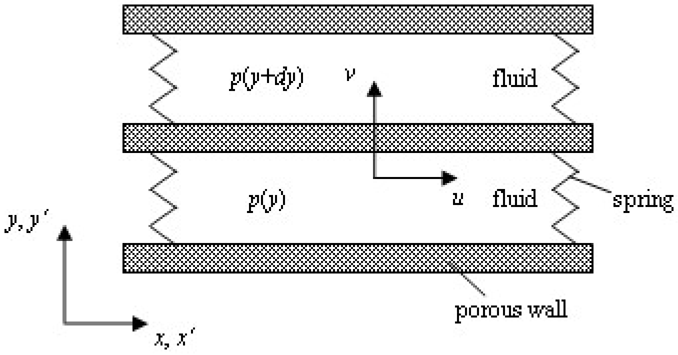


Fig. 1. Model of the smectic liquid crystal: *p* – pressure, *x*, *y* – coordinates, *u*, *v* – components of the velocity

If *x*-axis coincides with flow direction and *y*-axis is normal to the surface of layers of liquid crystal (Fig. 1), continuity, momentum and flow equations for the two-dimensional flow of the liquid crystal in the film lubrication bearing gap can be expressed as follows [1]:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0, \tag{1}$$

$$-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)-F'\frac{\partial w'}{\partial x'}=0, \tag{2}$$

$$-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+F'=0, \tag{3}$$

$$F'=\frac{1}{\lambda}\left(u'\frac{\partial w'}{\partial x'}+v'\frac{\partial w'}{\partial y'}-v'\right)=E\frac{\partial^2 w'}{\partial y'^2}-k\frac{\partial^4 w'}{\partial x'^4}, \tag{4}$$

where u and v are x and y components of the velocity of the lubricant, x, y, x', y' are coordinates, p is the pressure, μ is the viscosity, λ is the permeation coefficient of the layer, w' is the displacement of the lubricant layer, k is coefficient in force dimension [7], E is the modulus of elasticity, F' is the volume force function established according the principle of minimum energy.

These equations can be transformed into non-dimensional form [8]:

$$\frac{\partial u^*}{\partial x^*}+\frac{\partial v^*}{\partial y^*}=0, \tag{5}$$

$$-\frac{\partial p^*}{\partial x^*}+\frac{\partial^2 u^*}{\partial y^{*2}}=0, \tag{6}$$

$$-\frac{\partial p^*}{\partial y^*}+F^*=0, \tag{7}$$

$$F^*=N\left(u^*\frac{\partial w^*}{\partial x^*}+v^*\frac{\partial w^*}{\partial y^*}-v^*\right)=\frac{\partial p^*}{\partial y^*}=M\frac{\partial^2 w^*}{\partial y^{*2}}-K\frac{\partial^4 w^*}{\partial x^{*4}}, \tag{8}$$

where $x^*=x/B,\ y^*=y/H,\ u^*=u/U,\ v^*=\dfrac{vB}{UH},\ h^*=h/H,\ p^*=\dfrac{(p-p_a)H^2}{\mu UB},\ w^*=w/H$, H is the thickness of lubricant layer at the entrance of wedge, B is the length of analyzed area of lubricant layer, h is the thickness of lubricant layer, M, N and K are parameters characterizing specific effects (elastic compression of the layers, flow through the layer and elastic bending of the layer) occurring when the liquid crystals are used as lubricant.

$$M=\frac{EH^2}{\mu UB},\ N=\frac{H^4}{\mu\lambda B^2},\ K=\frac{kH}{\mu UB^5}, \tag{9}$$

$$\sigma^*_{yy}=-p+\tau^*_{yy}=-p+M\frac{\partial w^*}{\partial y^*}, \tag{10}$$

where σ^* is the normal stress, τ^* is the shear stress.

Eqs. (5-7) can be transformed into single-variable equation, which contains single independent variable – non-dimensional flow function Ψ [8]:

$$u^*=\frac{\partial\Psi^*}{\partial y^*},\ v^*=-\frac{\partial\Psi^*}{\partial x^*}. \tag{11}$$

$$N\frac{\partial^2\Psi^*}{\partial x^{*2}}=\frac{\partial^4\Psi^*}{\partial y^{*4}}. \tag{12}$$

After designating:

$$\xi=\sqrt{N}x^*,\ \eta=\frac{\sqrt[4]{N}}{\sqrt{x^*}}\left(y^*-y_0^*\right), \tag{13}$$

the flow function can be expressed as follows:

$$\Psi^* = \sqrt{\frac{\xi}{N}} f(\eta). \tag{14}$$

Function $f(\eta)$ must satisfy the following requirement [7]:

$$\left[f''' + \frac{1}{4}\eta(f - \eta f') \right] = 0. \tag{15}$$

Physical quantities expressed in new variables are presented as follows [8]:

$$u^* = f',\ v^* = -\frac{V(\eta)}{2\sqrt{\xi}},\ w^* = \frac{\sqrt{\xi}}{M} W(\eta),\ \tau^*_{yy} = \frac{W'}{\sqrt{N}},\ V(\eta) = f - \eta f' = 2W''. \tag{16}$$

Solutions of the last equations:

$$W = -\frac{\eta}{2} - \frac{\eta}{2} erf\left(\frac{\eta}{2}\right) - \frac{1}{\sqrt{\pi}} erf\left(-\frac{\eta}{2}\right),\ W' = -\frac{1}{2}\left[1 + erf\left(\frac{\eta}{2}\right)\right], \tag{17}$$

where *erf* is the error function.

After reduction of Eq. (14) and Eq. (16) to the form of Eq. (7) and further integration with respect to the variable η, the pressure can be determined:

$$p^* = -\frac{1}{2}\sqrt{N} erf\left(\frac{\eta}{2}\right) + F^*(\xi). \tag{18}$$

It can be obtained from Eq. (6) after its transformation, determining the derivative $\partial p^* / \partial \xi$ and then equating it to zero:

$$p^* = -\frac{1}{2}\sqrt{N} erf\left(\frac{\eta}{2}\right) + C, \tag{19}$$

where C is the constant obtained from boundary conditions.

It is obtained from Eqs. (16) and (17):

$$\tau^*_{yy} = -\frac{1}{2}\sqrt{N}\left[1 + erf\,\frac{\eta}{2}\right]. \tag{20}$$

In accordance with Eq. (10) it is possible to obtain stress value:

$$\sigma^*_{yy} = -\frac{1}{2}\sqrt{N} + C. \tag{21}$$

In case of conventional viscous fluid: $\sigma^*_{yy} \approx -1$ [1]. It can be stated that in the case of large values of permeation parameter (for example $N = 10^4$) there can be a 200-fold difference [8] in load-carrying capability of conventional lubricant (oil) layer and liquid crystal layer.

Experimental procedure

Despite the unique lubricating [5] and load-carrying properties of individual liquid crystals, their use as a lubricant is limited. The main reasons are high cost of liquid crystals and their temperature-dependent phase behavior. Therefore use of liquid crystals and oil mixtures are more promising approach for practical application of liquid crystals in real tribological systems. However dissipative properties of such systems are not studied yet.

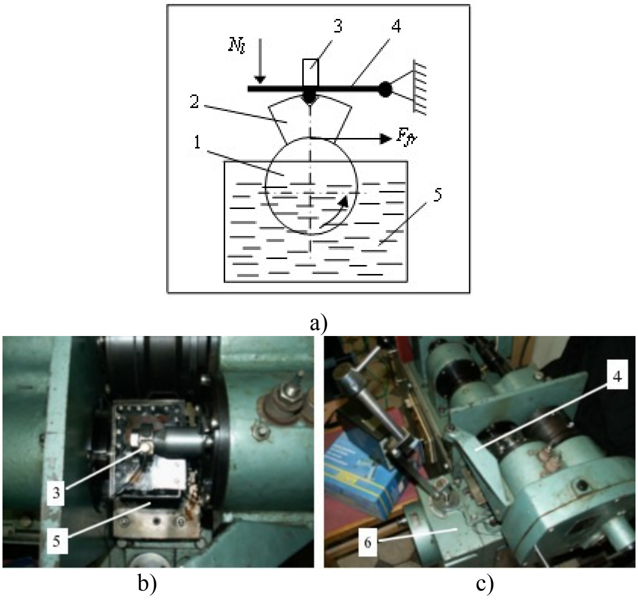
Vibration behavior of friction pair was investigated using a computerized tribometer [9] (Fig. 2). Steel friction pair rotating roller – fixed segment (Fig. 2a) was used under the boundary lubrication conditions. The segment was vertically loaded and oil bath lubricated. Known values of radial load can be applied in the tested friction pair through a lever 4 and a load unit 6 with a screw-spring system (not shown in Fig. 2).

Semi-synthetic mineral motor oil (SAE 10W/30) with and without liquid crystalline additive was used to lubricate friction pair. Cholesteryl oleate (oleic acid (unsaturated) cholesteryl ester) $C_{45}H_{78}O_2$ which exhibits smectic and twisted nematic phases was used as oil additive. Properties of liquid crystal can be described as follows: molecular weight 651.1, melting point 44 – 47 ºC. Concentration of liquid crystal in oil was 2 v/v %.

The mixtures of oil and liquid crystal were prepared as follows: oil and liquid crystal were simultaneously heated up to the melting point of the liquid crystal, mixed and cooled down to the room temperature.

Other conditions of the experiment were as follows: rotational speed of the roller – 320 rpm (frequency 5.3 Hz), sliding velocity – 0.82 m/s, load force – 1000 N (contact pressure is equal to 5 MPa).

A piezoelectric accelerometer (Brüel & Kjær mod. 4375, 0.1 – 16500 Hz useful range, 55 kHz resonance frequency) attached to the segment measured radial vibration of the segment. Brüel & Kjær LAN-XI Type 3660-D data acquisition hardware was used. The measured signal is amplified and filtered with low band pass filter at a 2 Hz cutoff frequency. Measured acceleration signal was double integrated using computer. Data analysis was performed with the aid of Brüel & Kjær Pulse Reflex software.



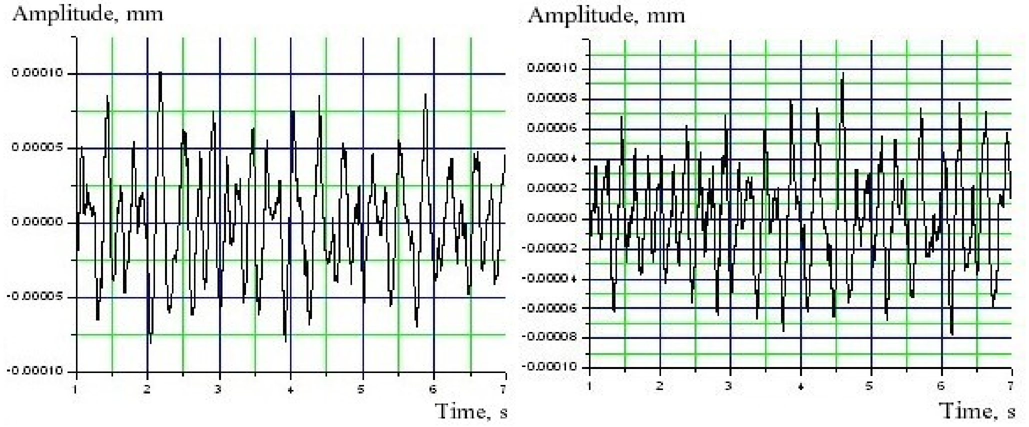
a)

b) c)

Fig. 2. Scheme of friction pair (a) and top view of a tribometer (b, c): 1 – roller, 2 – segment, 3 – accelerometer, 4 – load lever, 5 – lubricant bath, 6 – load unit, N_l – load force, F_{fr} – friction force

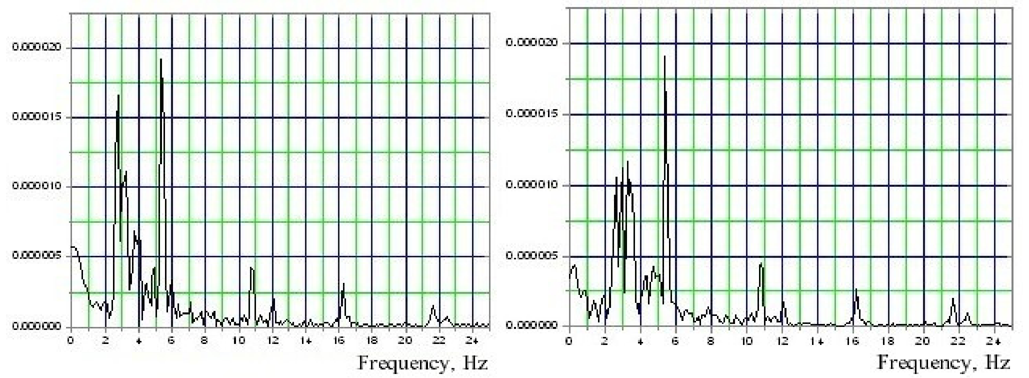
Results and discussion

Fig. 3 shows vibration amplitudes of the segment as function of test time. Amplitude spectra are presented in Fig. 4. Comparison of the results in Fig. 4a with those in Fig. 4 b indicates that vibration level is much smaller in low frequency range (less than 5 Hz) when oil with liquid crystal additive is used to lubricate friction pair. It was shown in [10] that friction process mainly affect vibration of friction pairs in the frequency range (0.25 – 0.75)f_b, where f_b is rotational frequency. Fig. 4 confirms that noticeable differences in vibration, due to change in lubricant composition, are related to vibration in the 2 – 4 Hz frequency range. The root mean square (RMS) values of vibration amplitude are presented in Fig. 5. It is possible to notice appreciable difference in vibration of the segment when motor oil with liquid crystalline additive was used to lubricate friction pair.



a) b)

Fig. 3. Segment vibration amplitude as function of test time: a) friction pair is lubricated with motor oil, b) friction pair is lubricated with motor oil containing liquid crystalline additive



a) b)

Fig. 4. Segment vibration amplitude spectra: a) friction pair is lubricated with motor oil, b) friction pair is lubricated with motor oil containing liquid crystalline additive

Conclusions

1. In the case of large values of permeation parameter the load-carrying capacity of liquid crystal layer can be more than 200-fold larger than in the case of oil.

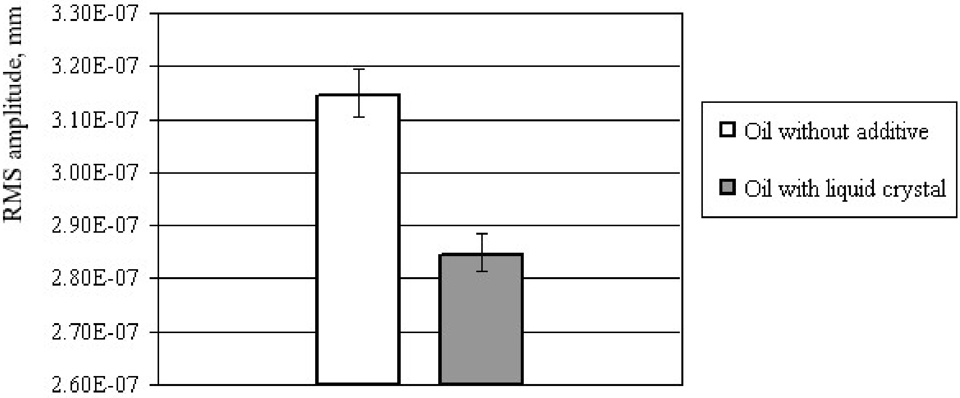


Fig. 5. RMS amplitude of the segment as function of lubricant composition

2. Liquid crystalline additive only affects the vibration of friction pair in low frequency range of 2 – 4 Hz.

3. Upon increasing the dissipativity of motor oil by the introduction of 2 v/v % cholesteryl oleate additive, the RMS amplitude of segment was reduced from 3.14×10^{-7} mm to 2.84×10^{-7} mm as compared with value obtained using motor oil without liquid crystal additive.

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