

Chapter 2

Oil Viscosity Monitoring

2.1 Introduction

The safety and reliability of tribosystems depend largely on the properties of the lubricating Materials and methods of its monitoring and diagnosis [1, 2]. Viscosity is one of the major physicochemical factors of quality and efficiency of oil, its capacity to provide the effective thickness of the lubricating layer between the friction surfaces which prevents the severe wear and failure of machinery [3, 4].

Viscosity of lubricating oils depends on temperature and load-speed conditions of their operation. For example, at high speeds, low loads, and low temperatures of operation of friction units, preference is given to oils with low viscosity, while oils with high viscosity operate better at low speeds, high loads, and elevated temperatures. Thus, an important aspect of ensuring the proper operation of tribosystems is the correct selection of oil, according to viscosity and its variation with temperature. As a rule, both the selection of lubricating oils and the development of the schedule and criteria for their changing are aspects of tribosystem design.

2.2 Oil Viscosity Characterization

In accordance with the technical requirements, the viscosity-temperature properties are characterized by viscosity index. To enhance the viscosity-temperature properties, thickening additives, e.g. polymer compounds, are applied. Polymethacrylates, polyisobutenes, products of polymerization of vinilbutyl ether, and others, are used for this purpose.

It is important not only to choose the oil properly, but to maintain its viscosity during operation, which requires regular monitoring of this parameter. If a change in viscosity is detected, subsequent analysis of the oil can identify the cause of such change. Either an increase or decrease in oil viscosity can result in the disturbance

of the bearing capacity of tribosystem. Increased oil viscosity can be the evidence of its thermal destruction, oxidation, additive decomposition, or contamination with fuel, water, coolant, etc. Decreased viscosity can be caused by ingress of fuel into the oil and cracking at high temperature. At the same time, certain processes can compensate viscosity change. For example, the oil of diesel engines is contaminated both by fuel, which decreases the viscosity, and soot, which increases it [5, 6]. Anyway, variation in the oil viscosity is often the first indicator of an important problem in the tribosystem.

Oil viscosity monitoring usually involves the determination of its relative variation in the course of operation relative to the viscosity of fresh oil. It should be taken into account that the viscosity of fresh oil according to standards can differ from its nominal value up to 20%, while a change in the viscosity by 10% during operation can often be critical. Therefore, preliminary inspection of fresh oil is important for obtaining the reference value of monitoring the viscosity. Table 2.1 lists the limits of viscosity variations, which are used for the monitoring of engine and industrial oils [5].

During viscosity measurement, it is necessary to take into account that lubricating oil, depending on its composition and state, can show the properties of the Newtonian fluid in which viscosity is independent on the stress or shear rate or a non-Newtonian fluid in which the viscosity depends on these factors. Base mineral and synthetic oils show the properties of Newtonian fluid. Oxidation and contamination of oil in the course of operation result in deviation of the viscosity properties from the properties of Newtonian fluid. With the introduction of viscous additives into the base oil, which decreases the temperature dependence of the viscosity, or with the formation of a water–oil emulsion, the oil becomes non-Newtonian fluid (Table 2.2) [7].

Table 2.1 Viscosity limits [5]

Limit	Engine oil** (%)	Industrial oil** (%)	Industrial oil operating in severe loading modes** (%)
Critical (upper)	+20	+10	+7
Preventive (upper)	+10	+5	+4
Preventive (lower)	−5	−5*	−5*
Critical (lower)	−10	−10*	−10*

Notes *Value is two times higher for oils with additives improving the viscosity index

**Limits for engine oil are indicated for the viscosity at 100 °C; for industrial oil, for the viscosity at 40 °C

Table 2.2 Viscous properties of lubricating oil [7]

Oil	Viscous properties
Fresh base oil Fresh oil containing no viscous additives	Newtonian fluid
Used oil without viscous additives Average level of oil oxidation Contaminated oil	Fluid similar to Newtonian one
Highly oxidized oil Used oil with viscous additives	Fluid similar to non-Newtonian one
Fresh oil containing viscous additives Oil–water emulsion	Non-Newtonian fluid

2.3 Laboratory Measurements of Viscosity

In the case of viscosity measurement, the concepts of the dynamic and kinematic viscosity are used. The dynamic viscosity η is the ratio of shear stress between the liquid layers to the transversal gradient of velocity. The kinematic viscosity ν , i.e., the liquid resistance to flow under gravitation, is the ratio of the dynamic viscosity to liquid density ρ_l .

At present, viscosity estimation is based on the measurement of resistance to motion of a body within the medium, or by flowing the test liquid through the channel with a given geometry. Capillary, rotational, and vibration viscometry and the falling ball method are widely practiced [8].

Determination of viscosity by the capillary method is based on the Poiseuille law and consists in measurement of the time of flowing of the known amount of liquid through the capillaries with a circular section at a given pressure drop. The standard capillary method for estimation of the kinematic viscosity (ASTM D445) involves measurement of the time of outflow of the defined volume of liquid under the force of gravity through a calibrated glass capillary [9]. For all viscometers, the time of liquid outflow is proportional to its kinematic viscosity. The kinematic viscosity (ν , mm^2/s) is computed by the formula

$$\nu = Ct,$$

where C is the calibration constant for the viscometer, mm^2/s^2 ; t is the arithmetic mean value of the outflow time, s. The relative error for standard capillary viscometers is $\pm 0.1\text{--}0.3\%$; and for operating devices, $\pm 0.5\text{--}2.5\%$.

The measurement of the dynamic viscosity provides for the presence of actuated parts in the viscometer (rotational, torsion, vibration viscometry; the falling ball method, and others).

In rotational viscometers, the liquid under investigation is placed in the clearance between two coaxial bodies (cylinders, cones, and spheres) or between plane and cone. One of the bodies rotates with frequency ω_r and torque M is transmitted through the liquid to another, stationary body [10]. The dynamic viscosity η is

determined by the torque at a given angular velocity or the angular velocity at a given torque by the formula

$$\eta = \frac{KM}{\omega_r},$$

where K is the constant dependent on the viscometer design.

The essence of the standard rotational method for the measurement of oil viscosity consists in recording the torque lag of an inner cylinder or cone of a gauge with the test oil at various gradients of the shear rate and in the computation of the shear stress and the dynamic viscosity:

$$\eta = \frac{\tau}{D},$$

where τ is the shear stress computed with the use of the measured relative angle of rotation of the measuring unit; D is the gradient of shear rate.

The relative error for the most widespread rotational viscometer lies within the limits of 3–5%.

In laboratory practice, the simple *falling ball method* is widespread, based on the measurement of velocity v of the steady motion of a body under the effect of gravity within the test liquid. The viscosity is computed by the Stokes formula

$$\eta = \frac{2}{9} \cdot \frac{(\rho_b - \rho_l) \cdot g R_b^2}{v_b},$$

where ρ_b and ρ_l are densities of the ball material and the test liquid, respectively; R_b is the ball radius; g is the acceleration of gravity; v_b is the ball velocity. The error of the method is ± 1 –3%.

Vibration viscometry is based on determination of variations in the parameters of the forced oscillations of a probe submerged into the studied medium. To measure viscosity of oil, an amplitude resonance form of the vibration method for viscometry is the most convenient. In this case, by tuning into the resonance, one can achieve maximum amplitude A of vibration; the amplitude of the vibration of the viscometer probe is the parameter used to determine the viscosity. In the general case, the dynamic viscosity is determined from the calibration relationship

$$\sqrt{\eta \rho_l} = \varphi(A),$$

where ρ_l is the oil density.

A nonstandard laboratory method of viscosity monitoring is ultrasonic viscometry based on the measurement of the dynamic viscosity by means of acoustic vibration with ultrasonic frequency. The submersion of vibrator, which performs free or forced vibration at the resonance frequency, into the liquid introduces additional losses related to the excitation of transverse acoustic waves within the liquid. This results in a decrease in the amplitude of forced vibrations or in

accelerated damping of free vibrations and variation of the resonance frequency of the vibrator. The measurement of the vibration parameters is used for evaluating the liquid viscosity. Ultrasonic viscometers measure the viscosity in a range from 10^{-3} to 500 Pa s with a relative error of 5%.

To fulfill the laboratory analysis, a wide spectrum of viscometers with high accuracy has been developed; however, their great size and high cost cause difficulties for their use for on-line monitoring. Therefore, the issue of the day is the development of new effective means for viscosity monitoring in real time. If viscosity measurement devices can be mounted into the oil circulation lines, the reliability of equipment operation will be increased, and the necessity of the periodic oil sampling for laboratory analysis will be eliminated, lowering maintenance costs.

2.4 Methods of On-Line Viscosity Monitoring

Viscosity monitoring devices mounted in oil circulation lines face some particular requirements: they must continuously give out reliable information on lubricating material viscosity without the need for frequent calibration or maintenance and must have a long term of operation within the hostile environment of an operating machine at high temperatures, pressure, and vibration. At the same time, they must be compact and have low cost. In the development of on-line viscosity meters, different approaches are used: methods using the macro-displacement of a body within the liquid, and the vibration and acoustic methods (Fig. 2.1) [8].

Methods for viscosity measurement using macroscopic displacement of a body within the liquid are based on modification of the laboratory measuring procedures. The capillary method is realized through mounting of capillary with a predefined

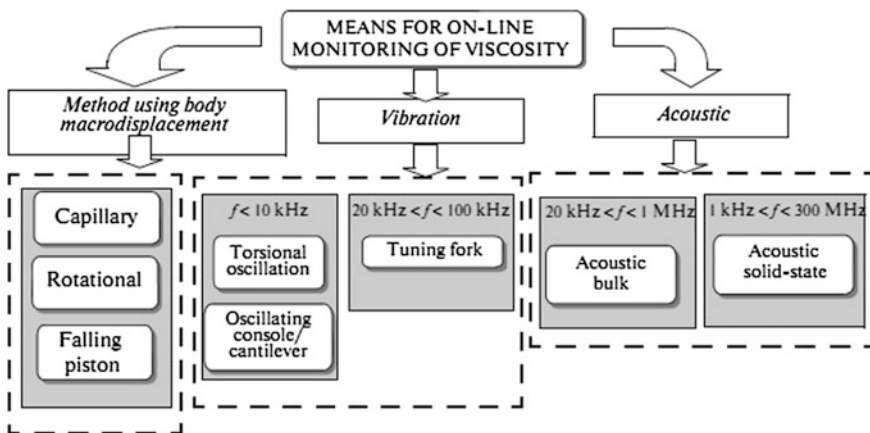


Fig. 2.1 Means for on-line monitoring of viscosity of the lubricating oils

configuration into the oil flow for measuring the pressure drop at a given flow velocity [11]. The application of this method is made difficult because the oil flow velocity is variable during machine operation and, in addition, the capillary becomes contaminated over time, decreasing measurement reliability.

Figure 2.2 presents a rotational viscometer based on Brookfield method [12], which can be mounted into the oil tank. The viscometer consists of rotating cylinder 1 fixed on the shaft 3 coaxially within motionless cylinder 2. The upper end of shaft 3 supports the measuring shaft 4 with which one end of the volute spring 5 is jointed. Its other end is fixed on the slotted disk 6 mounted on the shaft 7 of drive 9. The tested lubricating oil fills the viscometer chamber and produces viscous friction force in the oil layer within the circular clearance between the cylinders 1 and 2. The dynamic viscosity is proportional to the torque of this force, which is evaluated by the angle position of measuring shaft 4 relative to the shaft 7 of the drive. The angle position of the drive shaft is measured with slotted disk 6 and optoelectronic position sensor 8a. To determine the turning of the measuring shaft, indicator 10 and optoelectronic position sensor 8 are used.

The laboratory falling ball method was modified in the viscometer that uses the displacement of piston 1 in the liquid under the force of gravity to measure viscosity (Fig. 2.3). The piston goes up periodically by means of pneumatic mechanism 3. When the piston is in the elevated state, oil fills the measuring tube 2. Then the

Fig. 2.2 Rotational viscometer: 1, 2 rotational and motionless cylinders, respectively; 3 shaft; 4 measuring shaft; 5 volute spring; 6 slotted disk; 7 drive shaft; 8, 8a optoelectronic position sensors; 9 drive; 10 indicator [12]

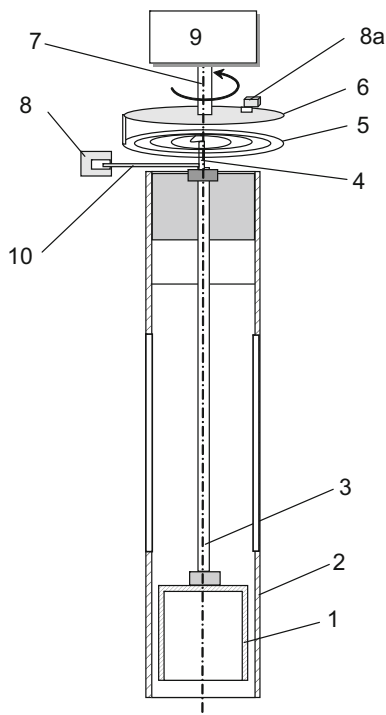
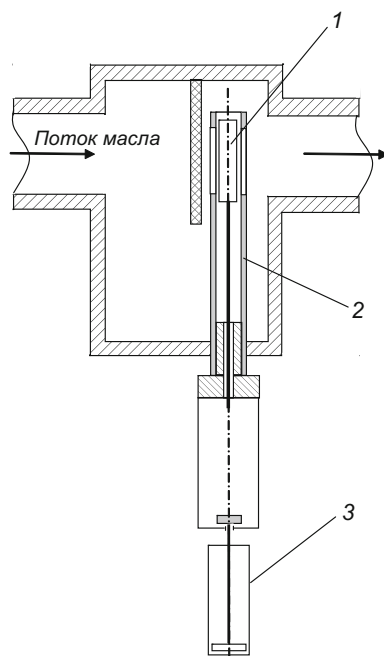


Fig. 2.3 Viscometer based on the method of the falling piston: 1 piston; 2 measuring tube; 3 pneumatic mechanism [13]



piston goes down and falls under the force of gravity, forcing out oil from the tube. The oil viscosity is evaluated by the time of the piston fall [13]. The disadvantage of the device is the necessity for mounting the piston in the strongly vertical position.

The method was perfected in a device using two electromagnetic coils 2 which enveloped the piston 1 made of ferromagnetic material (Fig. 2.4). The viscometer is mounted within the oil circulation line and oil fills the measuring chamber 4. The electromagnetic coils are switched on in turn, producing a force initiating the piston displacement to both sides along the measuring chamber. As the viscosity increases, the piston displacement becomes slower. The oil viscosity is evaluated by the time of motion of the piston between the coils. Because the piston displacement on both sides is forced, it is not subject to the effect of gravitation and oil flow [14].

The design of the viscometers based on macroscopic displacement, which are mounted into the oil circulation lines, is intricate due to their complexity, large size, and the presence of moving parts that decreases the reliability of the devices.

An alternative approach to on-line monitoring is presented by vibration and acoustic viscometers containing no moving parts subjected to wear.

Most vibration methods for on-line monitoring are based on the measurement of variation $\Delta A = A_2 - A_1$ in the amplitude of the natural oscillation of vibrator within the monitoring liquid, or of the oscillation bandwidth $\Delta f = f_1 - f_2$ [15] (Fig. 2.5). To monitor the dynamic viscosity, the phase difference for the signal exciting oscillations of vibrator and signal of its natural oscillations, as well as the rate of damping oscillations are measured.

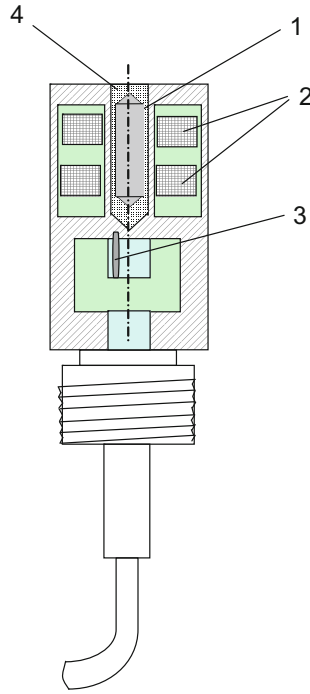


Fig. 2.4 Electromagnetic viscometer: 1 piston; 2 electromagnetic coils; 3 temperature device; 4 measuring chamber [14]

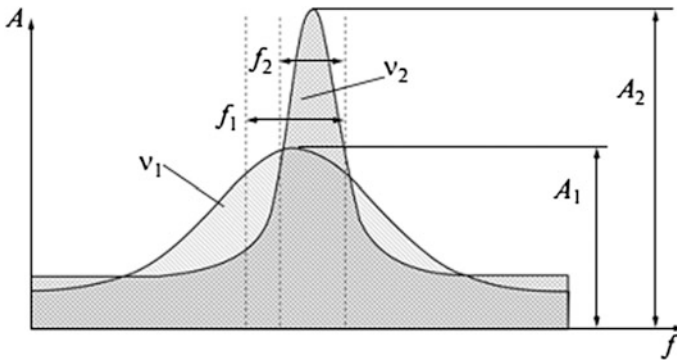


Fig. 2.5 Variation of parameters of vibrator oscillations as the liquid viscosity varies: A_1 , A_2 amplitude and f_1 , f_2 frequency of vibrator oscillations within the liquid with viscosity v_1 and v_2 ($v_1 > v_2$), respectively [15]

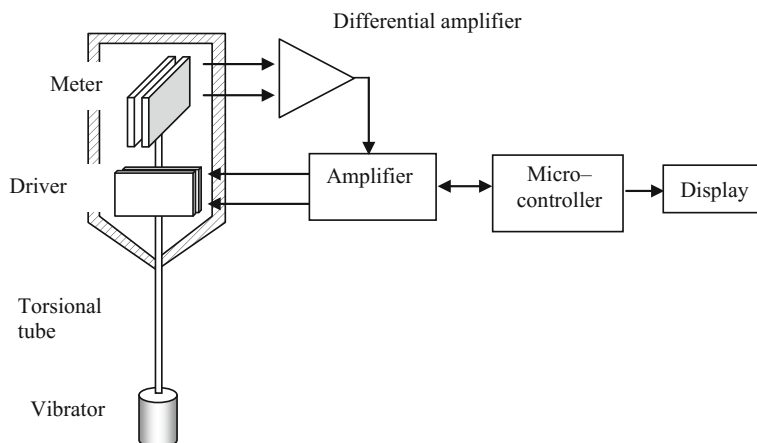


Fig. 2.6 Viscometer based on torsion oscillation [16]

Depending on the parameter used to evaluate viscosity, the device can have one of two configurations.

The viscometer based on torsion oscillations consists of vibrator (cylinder, plate, etc.) mounted at one end of the torsion tube (Fig. 2.6) [16]. At the second end of the tube, a drive and a turn meter are fixed. The drive, including two piezoelectric elements, is controlled by alternating voltage in such a way that vibrator produces torsion oscillations relative to the geometrical axis at the resonance frequency. The meter (the second pair of piezoelectric elements) records a signal characterizing the torsion oscillations. After amplification, the signal is processed with a microcontroller, whereby the phase difference between the voltage given on the piezoelectric elements of the drive and the signal from the meter, i.e. the damping factor proportional to the square root of the liquid viscosity, is determined.

The viscometer based on the use of vibrating cantilever has a beam made of a ferromagnetic material with a Teflon coating [17]. The cantilever 1 with the permanent magnet 3 is mounted over the electromagnet 2 (Fig. 2.7). The short pulse of current flowing via the electromagnet coil excites the bending oscillations of the cantilever at the frequency of its natural oscillations. Upon submergence into the liquid, oscillations are damped by the liquid resistance force, and the greater the liquid viscosity, faster they are damping. Oscillations of vibrating cantilever at a frequency of ~ 500 Hz are recorded by the same electromagnet coil and the dynamic viscosity of liquid is evaluated by the rate of their damping.

The disadvantage of the use of such a device is the contamination of the clearance between the cantilever and electromagnet with time and the ingress of ferromagnetic wear particles that disturb the operational efficiency of the device.

Tuning fork viscometers are based on the use of mechanical resonator usually operating at a frequency of <75 kHz [18]. The transducer includes the prongs 1 and 2 forming the tuning fork, which is submersed into the test liquid [19]. The prongs

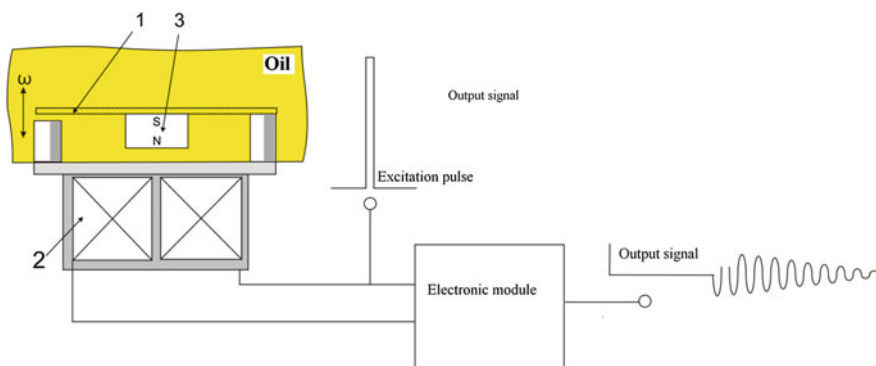
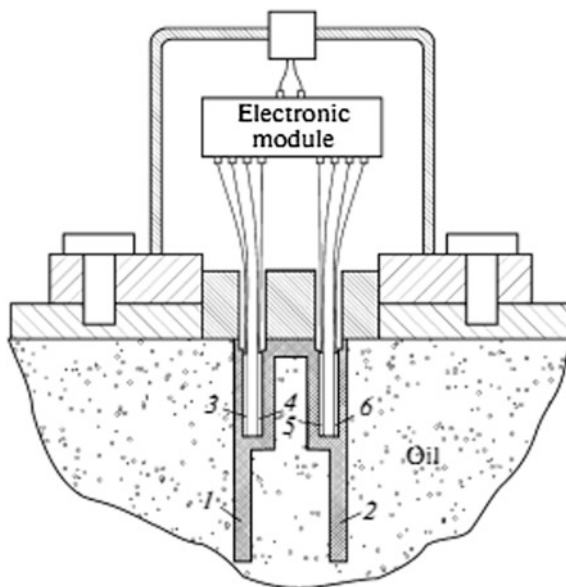


Fig. 2.7 Viscometer with bending oscillations of the cantilever: 1 cantilever; 2 electromagnet; 3 permanent magnet [17]

have channels in which piezoelectric ceramic elements 3, 4, 5, and 6 are mounted (Fig. 2.8). During the supply of voltage from the electronic module to piezoelectric elements 3 and 5, oscillations of the prongs are excited in the opposite phase. The signal describing the tuning fork oscillations is recorded by the piezoelectric elements 4 and 6. The oscillations depend on the shear resistance of the liquid and, consequently, on its viscosity. Tuning fork devices for monitoring the oil state in automotive engines are commercially produced and they can measure simultaneously the oil viscosity and degree of its contamination.

Fig. 2.8 Tuning fork viscometer: 1, 2 prongs; 3–6 piezoelectric elements [19]



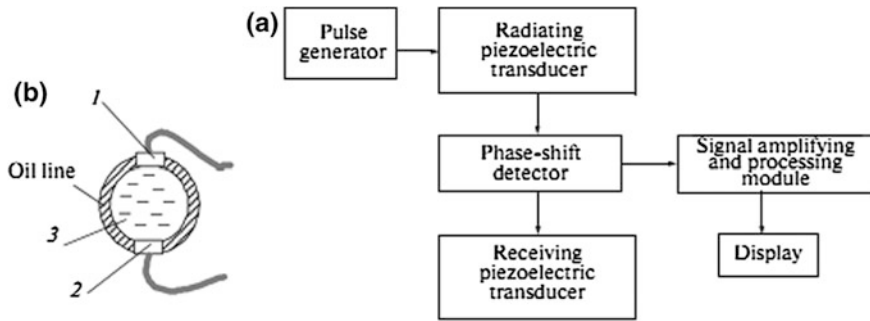


Fig. 2.9 Scheme of the acoustic viscometer **a** and transducers in the oil line **b**: 1, 2 radiating and receiving piezoelectric transducers, respectively; 3 test oil [20]

The principle of operation of *acoustic viscometers* is based on the excitation of elastic compression waves within the liquid.

Figure 2.9a shows the schematic of bulk acoustic viscometers including pulse generator, radiating and receiving piezoelectric transducers, and detector of the phase shift [20]. To measure viscosity the radiating 1 and receiving 2 piezoelectric transducers are mounted in the walls of the oil line (Fig. 2.9b). One of the sides of the radiating piezoelectric transducer is in contact with the test liquid. Pulses of the generator with a given frequency induce oscillations of the radiating piezoelectric transducer and excite the longitudinal acoustic wave within the test oil. The receiving piezoelectric transducer is opposite to the oscillator at a given distance and records the acoustic wave propagating through the liquid. The acoustic wave carries the information on the time of relaxation of liquid molecules, which depends on the molecular structure of the liquid and is expressed in the phase difference of the wave excited by the oscillator and the wave passed through the liquid and recorded by the receiver. The phase difference measured by the detector is used to determine the wave velocity, and the kinematic viscosity is computed according to the formula

$$v = \frac{V^2}{2\omega},$$

where V and ω are velocity and frequency of the acoustic wave, respectively.

The optimum operating frequency for acoustic viscometers lies in the range of 35–45 kHz. The main disadvantage of such devices is that the acoustic wave velocity depends not only on the viscosity of oil, but also on the level of its contamination by wear particles, air bubbles, etc.

Solid-state viscometers based on the use of acoustic waves present a promising class of devices [21, 22]. The physical principle of their operation is energy transfer by the acoustic shear wave from a waveguide having characteristic impedance of the material $Z_w = (\rho_w \mu)^{1/2}$ into the adjacent layer of the test liquid with wave resistance $Z_l = (\omega \rho_l \eta)^{1/2}$, where ρ_w and ρ_l are the densities of the waveguide and

the liquid, respectively and μ is the elastic modulus of the waveguide at shear. The energy transfer is proportional to the ratio Z_l/Z_w under condition $Z_l \ll Z_w$. In the application of solid-state viscometers, the notion of “acoustic viscosity” (a.v.) is used, that is the product of dynamic viscosity and density of liquid: $a.v. = \eta\rho_l$.

In viscometers with acoustic waves, piezoelectric materials are used to generate acoustic waves by an electric field. The waves are propagated through or over the surface of the substrate and then transformed back into the electric field for measuring. All variations in the characteristics of the propagation path affect velocity and/or amplitude of the wave which relate to the properties of the controlled medium.

Solid-state viscometers are classified by the mode of the wave propagating through the piezoelectric substrate. The fundamental modes of oscillation applied in acoustic wave devices for measuring liquid viscosity are thickness shear mode (TSM), shear-horizontal acoustic plate waves (SH-APW), and Love waves. These waves radiate an insignificant part of their energy into the liquid, which allows for devices to operate without substantial absorption in the liquid. The TSM and SH-APW waves are bulk, i.e., waves propagating within the entire volume of the substrate [21].

Devices based on TSM waves are the most simple and widespread. As is shown in Fig. 2.10a, such a device consists of the thin quartz disk with two circular electrodes deposited on the face surfaces. The application of voltage between the electrodes produces shear deformation of the crystal. The oscillating surface generates a laminar flow within the contacting layer of the liquid. The liquid layer involved in motion experiences delay by the phase which increases as the distance from the crystal surface rises. If the frequency of the applied voltage is varied, one can obtain the mechanical resonance and then half of the length of the acoustic wave is equal to the crystal thickness. In the case of the resonance, the maximum shear within the crystal is at its surfaces, and, consequently, the liquid viscosity exerts the greatest influence on the parameters of the crystal resonance. The shift of the resonance frequency and the change of the oscillation amplitude give information on the oil properties [22, 23]. Devices for the monitoring of engine oil viscosity based on TSM waves with resonance frequencies of 5–6 MHz are described elsewhere [24, 25]. The TSM viscometer is remarkable for its simplicity of production, resistance to harsh ambient conditions, and thermal stability. However, it was found that the output signal depends not only on viscosity, but also on the oil oxidation rate [25].

In the viscosity devices based on SH-APW waves, they use a thin piezoelectric plate with two interdigital transducers (IDTs) deposited at the opposite ends of one of the plate surfaces (Fig. 2.10b) [21]. The application of alternating voltage to IDTs causes the displacement of particles of the plate material exciting the acoustic wave. The crystal cut was selected in such a way that the application of electric field to IDTs generates shear waves with shear-horizontal polarization, so the direction of particles shift is normal to the direction of wave propagation and parallel to the sensitive surface. The wave is propagated via the plate, and on the IDTs of the other

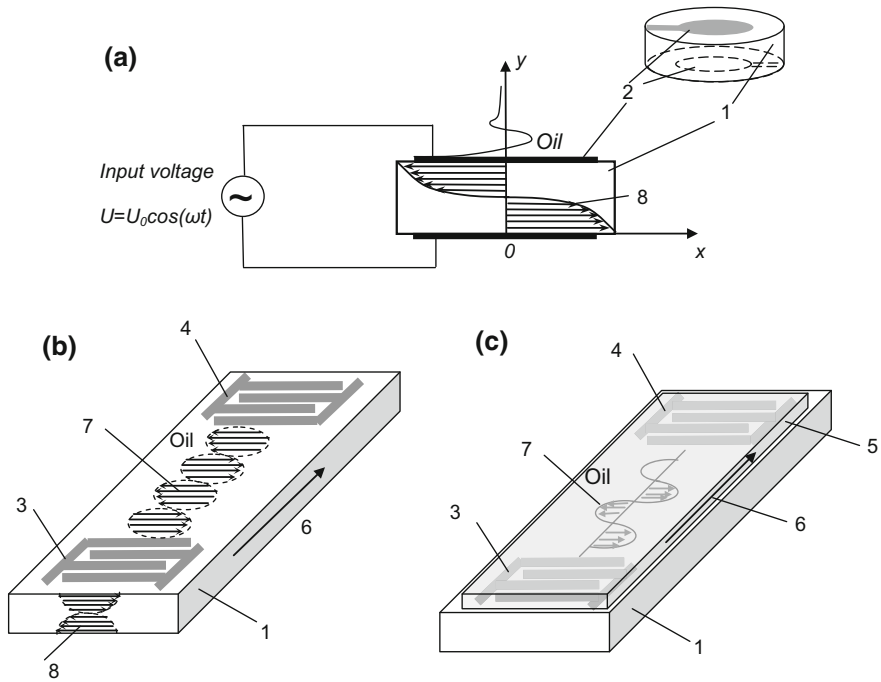


Fig. 2.10 Solid-state acoustic viscometers based on volume TSM [21] **a** and SH-APW waves [21] **b** and surface Love waves [27] **c**: 1 piezoelectric plate; 2 electrodes; 3, 4 input and output IDTs; 5 waveguide layer; 6 direction of wave propagation; 7 surface displacement; 8 volume displacement

end of the plate the mechanical energy of the acoustic wave is transformed into the electrical one. The operating frequency of the viscosity device is 25–200 MHz. The use of such a viscometer to monitoring the lubricating oil viscosity is described elsewhere [22, 26].

Devices based on the use of surface acoustic waves with horizontal shear polarization (SH-SAW), in which the displacement of particles of the plate material occurs within the plane of the crystal surface, are also known (Fig. 2.10c) [27]. In the common case, it is impossible to obtain purely horizontal shear waves; a part of the energy is lost with the volume acoustic wave which is propagated perpendicular to the surface. To decrease the energy loss, a special layer is deposited at the surface of the piezoelectric plate with IDTs. The speed of the shear wave propagation within this waveguide layer is lower than within the plate; as a result, the acoustic energy is concentrated within this layer. Thus, conditions arise for the propagation of so-called Love waves via the layer. The sensitivity of such acoustic waves to processes occurring at the surface is higher than in the case of common SH-SAW oscillations. In spite of the small sizes and the implementation in the form of chips, viscometers based on acoustic waves have a high cost because of the expensive

materials used for production of the acoustic waveguides. In addition, the high operating frequencies (1–200 MHz) require the use of complicated electronics. The devices are sensitive only to properties of thin layer of oil at the interface area because the depth of penetration of the acoustic wave into the liquid is inversely proportional to the square of frequency. The use of acoustic devices is limited to high viscosities because at oscillation with high frequencies, high molecular liquids have the tendency to behave as gels since the oscillation frequencies of molecules of such liquids are lower than the oscillation frequencies of the device.

2.5 Viscosity Sensor Based on Magneto-Elasticity

The main drawback of solid-state acoustic viscometers is that they are too expensive to be widely used; this is due to the necessity of using the expensive materials to fabricate acoustic waveguides and relatively expensive electronic components necessary to generate and control the high operating frequency. In addition, owing to the high operating frequency, these devices are sensitive to the fluid properties only in the thin layer that contacts the surface of the sensor. When high-frequency elastic waves propagate in high-molecular fluids, the latter start to show the behavior of gels and the gage readings may reflect inadequately the viscosity properties of the oil.

In parallel with solid-state sensors based on acoustic waves, magnetoelastic viscosity sensors are currently under development; they operate at lower frequencies.

2.5.1 *Magnetoelastic Viscometry Technique*

The magnetoelastic viscometry method [28] is based on the mutual effect of the magnetization and elastic deformations of the medium, which appears as variations in the dimensions and shape of the specimen when it is magnetized (magnetostriction) and as changes in the magnetization of the specimen when it is deformed (the magnetoelastic effect or Villari effect). The method involves the excitation of a longitudinal standing elastic wave in a sensitive element by generating an alternating magnetic field in the zone of its location with a frequency equal to the frequency of the natural oscillations of the element.

The theoretical model of the magnetoelastic viscosity sensor is based on the equation of longitudinal oscillations of thin elastic plate affected by the alternating magnetic field and the friction force that is applied to the plate immersed in the viscous liquid. For a plane wave, which propagates along the Y axis, the equation that describes the longitudinal oscillations of the plate lying in the YZ plane and oscillating in the direction of the Y axis is

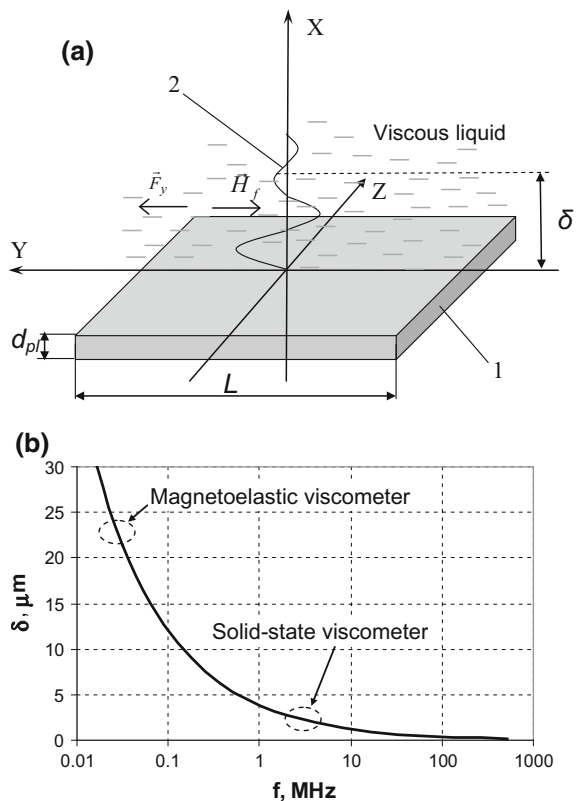
$$\rho_{pl} \frac{\partial^2 u_y}{\partial t^2} = \frac{E_{pl}}{1 - \sigma_{pl}^2} \frac{\partial^2 u_y}{\partial y^2} \quad (2.1)$$

where ρ_{pl} is the plate material density; E_{pl} and σ_{pl} are the Young's modulus and Poisson's ratio of the plate material, respectively; and u_y is the component of displacement vector of the plate particles along the Y axis under the effect of the external force that is applied per unit of the plate surface area. In addition to longitudinal waves that are excited by oscillations of the plate in the direction of the Y axis, rapidly damping transversal or shear waves exist in the viscous liquid, propagating along the X axis; the particles in the waves move along the Y axis (Fig. 2.11).

The equation of the motion of a viscous liquid in the vicinity of the plate surface, or the Navier-Stokes equation, can be presented in the form of the diffusion equation:

$$\frac{\partial v}{\partial t} = \frac{\eta}{\rho_l} \frac{\partial^2 v}{\partial x^2} \quad (2.2)$$

Fig. 2.11 Magnetoelastic plate under the effect of AC magnetic field \vec{H}_f and friction viscous force \vec{F}_y **a**: 1 plate, 2 shear wave damped by viscous liquid; dependence of shear wave penetration depth δ in a liquid on operation frequency **b**



where v is the liquid velocity; η is the liquid dynamic viscosity; and ρ_l is the liquid density.

The liquid velocity in the vicinity of the oscillating plate can be written as the following periodic function:

$$v = s_0 e^{i(kx - \omega t)} = s e^{ikx} \quad (2.3)$$

Based on Eqs. (2.2) and (2.3), we derived the following dependence of the liquid velocity on the distance to the surface of the oscillating plate (Fig. 2.11):

$$v = s \frac{\sin[k(d_{pl} - x)]}{\sin(kx)},$$

where $k = \frac{1+i}{\delta}$, d_{pl} is the plate thickness; and δ is the depth of the penetration of excitation induced by plate oscillations into the liquid, which can be estimated from the following equation:

$$\delta = \left(\frac{\eta}{\pi \rho_l f} \right)^{1/2}, \quad (2.4)$$

where η is the liquid dynamic viscosity, ρ_l is the liquid density, and f is the oscillation frequency of the plate.

When moving away from the oscillating plate, the amplitude of transversal waves damps according to the exponential law; the depth of the penetration of oscillations into the liquid diminishes with increasing frequency and rises with increasing liquid viscosity.

Figure 2.11b shows the dependence of the depth of the penetration of the shear wave into the lubricating oil with $\eta = 40$ mPa s and $\rho_l = 870$ kg/m³ on the oscillation frequency of the plate.

The friction force applied to the oscillating plate is directed along the Y axis and depends on viscosity and changes in the shear rate on the plate surface according to the Newton law:

$$F_y = \eta \left(\frac{\partial v}{\partial x} \right)_{x=0} \quad (2.5)$$

Equation (2.1), describing the longitudinal oscillations of the plate with account for the friction force becomes

$$\rho_l \frac{\partial^2 u_y}{\partial t^2} = \frac{E_{pl}}{1 - \sigma_{pl}^2} \frac{\partial^2 u_y}{\partial y^2} - F_y \quad (2.6)$$

A standing wave appears in the oscillating plate; when one edge of the plate is fastened, the equation of the wave is

$$u_y = 2Pe^{-i\omega_n t} \cos \frac{n\pi y}{2L} \quad (2.7)$$

where P is the amplitude of the standing wave and L is the plate length.

Using the Eqs. (2.1)–(2.7), we derive the following relation for estimating the natural frequency f_a of oscillations of the plate in nonviscous medium or air:

$$f_a = \frac{n}{4L} \sqrt{\frac{E_{pl}}{\rho_{pl}(1 - \sigma_{pl}^2)}}, \quad n = 1, 2, 3, \dots \quad (2.8)$$

Thus, the natural frequency of the magnetoelastic plate depends on its dimensions and the material properties.

Similarly, using the Eqs. (2.6) and (2.7), one may estimate the natural frequency of oscillations of the plate in a viscous liquid with account for the rheological properties of the latter.

The natural oscillations of the plate immersed in a viscous liquid located in the YZ plane and oscillating in the direction of the Y axis are harmonic oscillations with exponentially damping amplitude (Fig. 2.12); they are described by the following equation:

$$y(t) = Ae^{-\xi\omega_a t} \cos(\omega_l t + \varphi), \quad (2.9)$$

where A is the oscillation amplitude; ξ is the damping viscosity factor; ω_a is the circular frequency of natural oscillations of the plate in air (without friction); ω_l is

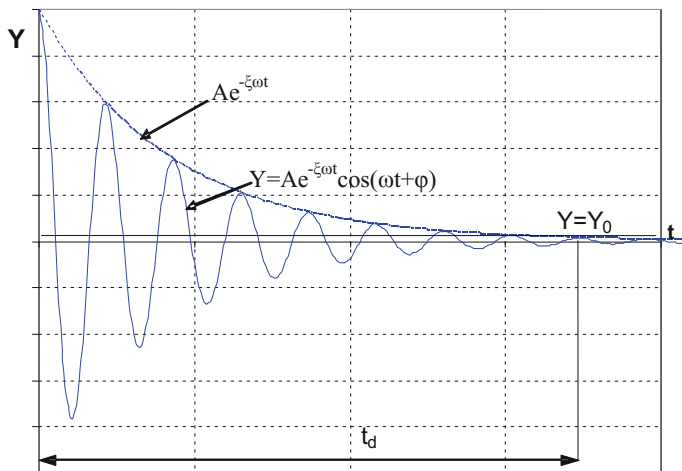


Fig. 2.12 Longitudinal oscillations of plate immersed in liquid

the frequency of natural oscillations of the plate in the liquid, $\omega_l = \omega_a \sqrt{1 - \xi^2}$ and φ is the phase shift.

The rate of decay of the longitudinal oscillations of the plate immersed in the viscous liquid is described by the damping factor ξ , which depends on the liquid viscosity. When the plate is immersed in the liquid, the frequency f_l of its natural oscillations or the resonance frequency diminishes by Δf :

$$\Delta f = f_a - f_l = \frac{\sqrt{\pi f_a}}{2\sqrt{2}\pi\rho_{pl}d_{pl}}(\eta\rho_l)^{1/2} \quad (2.10)$$

Thus, when the frequency shift Δf is measured, the “acoustic viscosity,” *a.v.*, or the product of the oil viscosity and oil density can be found as follows:

$$a.v. = \eta\rho_l = \Delta f^2 \frac{8\pi\rho_{pl}^2 d^2}{f_a} = B \frac{\Delta f^2}{f_a} \quad (2.11)$$

where B is a constant that depends on the density and thickness of the magnetoelastic plate.

Compared to viscosity, the oil density varies only slightly during operation. In this case, the following relation can be used to estimate the dynamic viscosity:

$$\eta = \frac{a.v.}{\rho_l} = B \frac{\Delta f^2}{f_a \rho_l} \quad (2.12)$$

Among the important problems that arise when developing magnetoelastic instrumentation for viscosity monitoring is the temperature dependence of the frequency of natural oscillations of the plate. It results from the temperature dependences $\rho_{pl}(T)$ of the plate material density and $L(T)$, $d(T)$ of the plate dimensions. Thus, temperature compensation has to be provided when developing methods for measuring the oil viscosity.

In addition to estimation of the rheological properties of liquids by the difference of the frequencies of natural oscillations of the plate in air and in the liquid being monitored, acoustic solid-state sensors involve a method based on analysis of the damping rate of the oscillation amplitude, i.e., measurement of the damping factor [29, 30]. Apparently, this method can also be applied in magnetoelastic sensors for on-line diagnostics.

2.5.2 Magnetoelastic Viscometer

Sensitive elements made of amorphous metals, so-called metallic glasses, are promising for application in magnetoelastic sensors for on-line monitoring. These

materials are alloys with an amorphous structure that results from very rapid cooling of a melt [31].

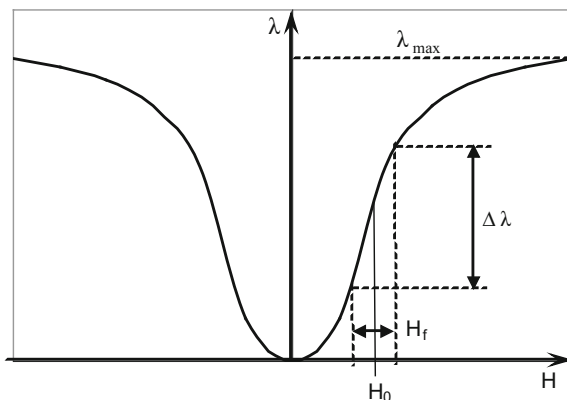
The relatively cheap amorphous ferromagnetic alloys $\text{Fe}_{40}\text{Ni}_{38}\text{Mo}_4\text{B}_{18}$ (Metglas 2826 MB) and $\text{Fe}_{81}\text{B}_{13.5}\text{Si}_{3.5}\text{C}_2$ (Metglas 2605SC) with the high ultimate strength (1000–1700 MPa) are the most widely used in miniature sensors. In addition, they possess magnetostriction (relative elongation $\lambda = \Delta L/L$ under the effect of magnetic field) of the order of 10^{-5} and high coefficient of transformation of magnetic energy into elastic one of 0.98, whereas such coefficient of most widely applied nickel alloys is ≈ 0.4 . The use of this material allows designers to make sensors more portable.

It should be noted that the elasticity of these materials depends on the strength of the applied magnetic field. In order to optimize the selection of the operating point of the sensitive element, i.e., to obtain the maximal change in the relative elongation under the effect of alternating field, a stationary bias magnetic field is additionally applied. Figure 2.13 shows the dependence of the magnetostriction λ on the strength H of the stationary bias magnetic field [32]. It is seen that the use of a stationary bias field with the strength H_0 and the excitation of oscillations by an alternating magnetic field with the amplitude H_f yield variations in the relative elongation of the sensitive element equal to $\Delta\lambda$. The strength of the applied magnetic field apparently governs the frequency and amplitude of the natural oscillations of the sensitive element (Fig. 2.14) [33].

Researchers from the V.A. Belyi Metal–Polymer Research Institute of NAS of Belarus and the Korea Institute of Science and Technology have developed a magnetoelastic viscometer (Fig. 2.15) that comprises a probe and electronic unit.

The viscometer probe consists of a viscosity transmitter–sensitive magnetoelastic plate (1) $37 \times 6 \times 0.03$ mm in size made of amorphous metallic glass Metglas 2826 MB—and an electromagnetic coil (2) (Fig. 2.15a). The latter serves to generate signal that excites mechanical oscillations of the plate and to measure the signal induced by the plate oscillations, which attenuate as they are damped by viscous oil (4). A platinum thermometer (3) is used to measure the oil temperature,

Fig. 2.13 Dependence of magnetostriction on strength of bias magnetic field



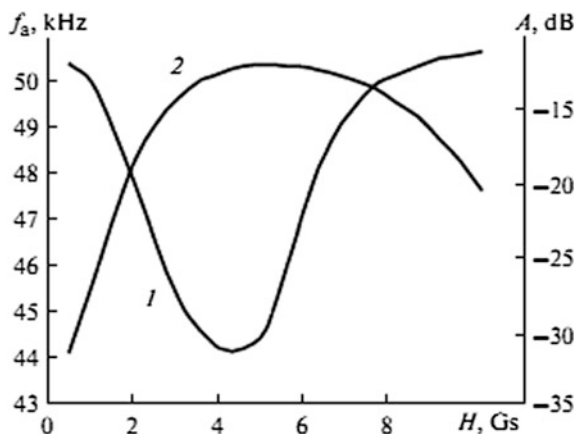


Fig. 2.14 Dependence of the resonance frequency f and amplitude of natural oscillations A of the sensitive magnetoelastic element on the strength of the stationary bias field [33]

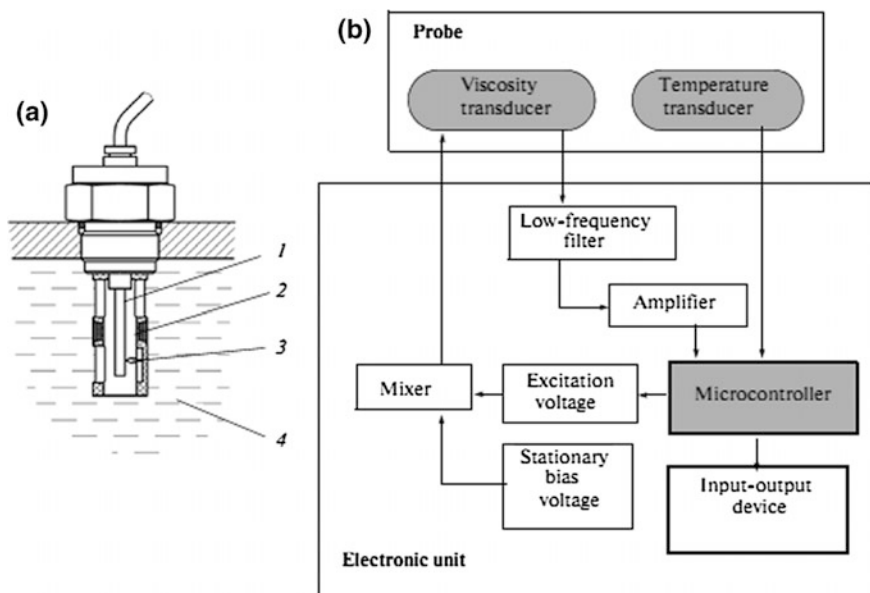


Fig. 2.15 Design of the probe **a** and block diagram of the viscometer **b** of magnetoelastic viscometer: 1 magnetoelastic plate, 2 electromagnetic coil, 3 thermometer, 4 oil

which is important when interpreting viscosity data, and to perform temperature compensation. The probe case has holes through which oil flows to the thermometer (3) and magnetoelastic plate (1). To protect the magnetoelastic element against mechanical damage end of the case that is immersed in the oil is equipped with

protective mesh. Using the threaded joint and gasket ring, it is possible to mount the probe into a tank containing the oil being monitored or into a pipe through which the oil is pumped.

The determination of viscosity is based on finding the resonance of the oscillations of the plate immersed into the monitored oil and analysis of the characteristics of the signal. The viscometer implements both the method for determining the viscosity by variations in the resonance frequency and the method based on the analysis of the decay curve of the oscillation amplitude.

The program implements the following measurement algorithm. A direct current passes the turns of an electromagnetic coil (2) and induces a stationary magnetic field that magnetizes the elastic element (1), thus providing conditions for its effective operation. Simultaneously, alternating current passes the coil turns; it induces an alternating magnetic field that excites longitudinal elastic oscillations of the magnetoelastic element. Then the alternating current is switched off and the element continues oscillating at its natural frequency, which depends on the oil viscosity. The elastic oscillations of the element (1) generate alternating current in the coil (2); its frequency f_l corresponds to the frequency of oscillations of the element.

To determine the frequency f_l the frequency of the inducing alternating current has to be varied or scanned within the $f_{l,min}-f_{l,max}$ range. The edge frequencies of this range are found from the limiting values η_{min} and η_{max} of the monitored viscosity of lubricating oils using the formula (2.10):

$$f_{l,min}(\eta_{max}) = f_a - \Delta f(\eta_{max}) = f_a - \frac{\sqrt{\pi f_a}}{2\sqrt{2}\pi\rho_{pl}d_{pl}}(\eta_{max}\rho_l)^{1/2},$$

$$f_{l,max}(\eta_{min}) = f_a - \Delta f(\eta_{min}) = f_a - \frac{\sqrt{\pi f_a}}{2\sqrt{2}\pi\rho_{pl}d_{pl}}(\eta_{min}\rho_l)^{1/2}.$$

When using the method of determining viscosity by variations in the resonance frequency, the frequency f_{ex} is recorded, at which the resonance occurs, i.e., $f_l = f_{ex}$. The compensation of the temperature dependence of the frequency of the natural oscillations of the magnetoelastic element involves the determination of the frequency $f_a(T)$ of its natural oscillations in air from the analytical dependence stored in a microcontroller. This value of the frequency corresponds to the measured temperature T and is used to correct the shift of the frequency $f_l(T)$ of the damped oscillations in the oil:

$$\Delta f_l(T) = f_a(T) - f_l(T) \quad (2.13)$$

The acoustic viscosity *a.v.* is calculated using the formula (2.11).

The method based on the analysis of the decay curve of the oscillation amplitude involves finding the time t_d for damping of oscillations at the resonance frequency

to stop (Fig. 2.12). In this case the resonance frequency depends on the frequency at which the greatest number of pulses occurs. The damping time is governed by the number of oscillations of the plate or the number of pulses recorded with amplitude exceeding the preset limit Y_0 . The viscosity is estimated from the preregistered calibration dependence $a.v.(N)$. Data are measured and processed by a microcontroller C8051F021. The display of the electronic unit shows the oil viscosity and the temperature at which the viscosity has been measured.

2.5.3 Experimental Results

Verification of data measured by two developed techniques

We have analyzed the theoretical and rated temperature dependencies of kinematic viscosity of synthetic oils. The theoretical dependencies were found in accordance with ASTM D341 for the liquids with above 2 cSt viscosity using the formula [34]:

$$\lg(\lg(v + 0.7)) = a - b \cdot \lg(T + 273), \quad (2.14)$$

where T —oil temperature, °C; v —kinematic viscosity, cSt; a, b —coefficients found from kinematic viscosity values at two specified temperatures (40 and 100 °C).

The experimental data on kinematic viscosity were obtained by recalculation of the measured acoustic viscosity as follows:

$$v = \frac{a.v.}{\rho_l^2}. \quad (2.15)$$

Figure 2.16 illustrates the theoretical and experimental temperature dependencies of the kinematic viscosity obtained by the technique based on the resonant frequency shift (data for synthetic oil PAO4 are presented in Fig. 2.16a) and by the analysis of the amplitude decay curve (for synthetic oil PAO8, Fig. 2.16b).

The results have proved that the technique of viscosity measurement based on the oscillations decay rate yields more accurate data ($\pm 5\%$ error) than that based on the resonant frequency shift ($\pm 15\%$ error).

Estimation of correlation between the readings of magnetoelastic, capillary and solid-state acoustic viscometers in testing base synthetic and mineral oils

Viscosities of four synthetic (PAO4, PAO6, PAO9 and PAO40) and two mineral base oils (P-96 and P-480) were evaluated. Table 2.3 presents the kinematic viscosity values measured at 40 °C by capillary viscometer Cannon-Fenske Viscometer (Glass Capillary Viscometer, ASTM D446) following the standard method (ASTM D445), acoustic viscosity values measured by magnetoelastic

Fig. 2.16 Theoretical and experimental temperature dependencies of kinematic viscosity using the technique of viscosity estimation from the resonant frequency variation **a** and the analysis of the amplitude decay curve **b**

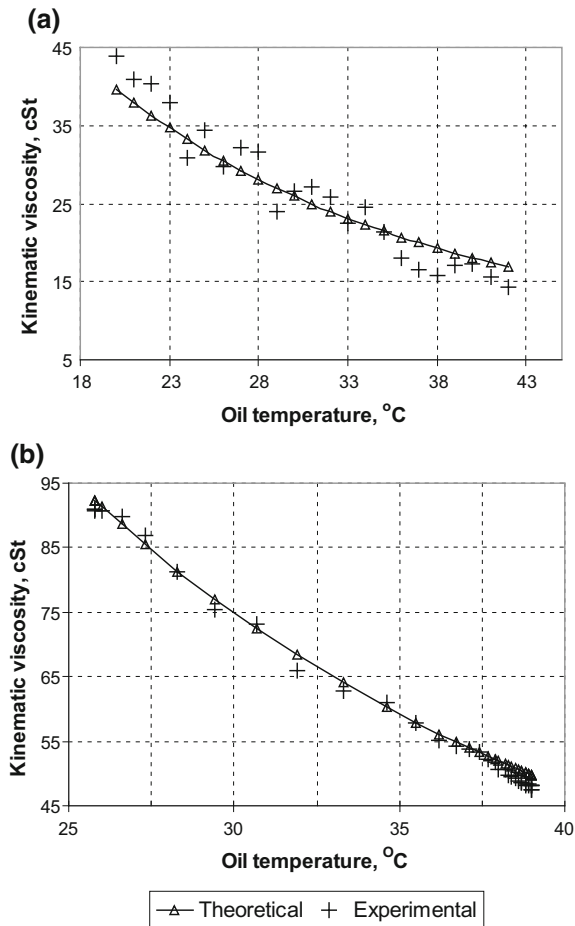


Table 2.3 Measurement results of oil viscosity values by capillary, magnetoelastic and solid-state viscometers at 40 °C

Viscometer	Measured parameter	Oils under test					
		PAO 4	PAO 6	PAO 8	P-96	PAO 40	P-480
Capillary viscometer	v, cSt	17.3	30.3	47.7	96.2	392.6	496.6
Magnetoelastic viscometer	a.v., cP kg/cm ³	12.7	21.8	30.0	70.0	299.6	417.6
	v, cSt	19.3	32.6	44.2	92.1	423.6	533.2
Solid-state viscometer	a.v, cP kg/cm ³	12.8	20.2	31.2	79.2	310.0	468.2
	v, cSt t	19.5	30.2	45.9	104.2	438.3	597.8
ASTM D 891-09	ρ _l , g/cm ³	0.811	0.818	0.824	0.872	0.841	0.885

viscometer using the procedure of analyzing the decay rate of oscillations, and by solid-state acoustic viscometer (ViSmart, Vectron Int.). The table also lists the corresponding values of kinematic viscosity calculated by formula (2.15) with account of oil density measured under ASTM D891-09.

The comparison of measurement results shows that the data obtained by the developed viscometer are the closest to viscosity measured by the capillary technique within the whole measurement range 17–500 cSt. In contrast, the solid-state acoustic viscometer has shown less validity in measuring viscosity above 300 cSt. Its readings are much higher the expected ones, evidently because the layer of viscous oil on the sensing surface of the viscometer behaves like a gel under high operating frequencies (5.3 MHz).

Changes in oil viscosity during artificial aging

Oil samples were prepared by artificial aging. The gear oil GS Caltex “Meropa 220” was oxidized at temperature 148 °C. The oxidation process was stopped for the nighttime. In the course of oil oxidation, the samples were taken after 0, 8, 26 and 35 h. Viscosity was measured using the magnetoelastic, solid-state, and glass capillary viscometers at 40 °C (Table 2.4).

The comparison of the test results proves that the solid-state viscometer shows higher viscosity values than those measured by the magnetoelastic and capillary viscometers. This can be attributed to variations in chemical structure during artificial aging and increased polarity of molecules, which changes interfacial interactions between the oil and sensitive surface of the solid-state viscometer. Since the viscometer is sensitive to variations in properties within a very thin oil layer, these interactions at the interface can affect the readings.

Effect of PMMA viscosity index improver on viscometer readings

To study the effect of PMMA VI improver on viscometer readings we have prepared the samples of synthetic base oil PAO6 with improver in concentrations 3, 6

Table 2.4 Viscosity monitoring in the course of oil aging

Oil sample code	Sample#1	Sample#2	Sample#3	Sample#4
Duration of oxidation, Hours Days	0	8	26	35
	0	1	3	4
Capillary viscometer ASTM D 446, v, cSt	236	239	245	247
Solid-State viscometer a.v, cP g/cm ³ v, cSt	201	205	210	212
	248	253	259	262
Magnetoelastic viscometer a.v, cP g/cm ³ v, cSt	197	198	199	204
	243	244	246	251

Table 2.5 Kinematic viscosity of oil samples with VI improvers

VI improver	M _w ^a , Daltons	Kinematic viscosity, cSt at 40 °C			
		C _m ^b = 0%	C _m = 3%	C _m = 6%	C _m = 9%
PMMA-1	40,311	30.40	34.18	38.16	42.62
PMMA-2	60,795	30.40	33.40	37.14	41.78
PMMA-3	155,259	30.40	34.40	39.04	44.55
PMMA-4	530,537	30.40	33.31	37.16	42.42
kinematic viscosity, cSt at 100 °C					
PMMA-1	40,311	5.98	6.68	7.54	8.47
PMMA-2	60,795	5.98	6.68	7.54	8.60
PMMA-3	155,259	5.98	7.04	8.34	9.94
PMMA-4	530,537	5.98	7.15	8.67	10.50

^aMolecular weight^bConcentration of VI improver

and 9 wt%. Four different modifications of PMMA (PMMA-1, PMMA-2, PMMA-3 and PMMA-4) with different molecular weights were under testing to estimate the influence of molecular weights of the VI improver on viscometer data (Table 2.5). The molecular weights of the VI improvers were measured using GPC (Gel Permeation Chromatography, HLC-8320GPC) at 40 °C temperature.

The improver molecular weight effect on kinematic viscosity at 40 and 100 °C was estimated by Capillary Viscometer Cannon Fenske (ASTM D445) (Table 2.5). As it was expected, kinematic viscosity increased at 100 °C with increasing molecular weight and content of the VI improver. Meanwhile, at 40 °C viscosity increased with growing concentration of the VI additive but without any correlation between the increment in molecular weight and viscosity. Obviously, the VI improvers have different temperature behaviors, which is evident at lower temperature (40 °C), while their application is intended for higher temperature (100 °C).

Viscosity of the test samples was also measured by the magnetoelastic and solid-state viscometers at 40 °C. The absolute viscosity was determined from the measured acoustic viscosity values using formula

$$\eta = \frac{a.v.}{\rho_l}.$$

The analysis of measurement results of the absolute viscosity of the test oils with addition of PMMA-1 and PMMA-2 in concentrations 3, 6 and 9 wt% shows that the data determined using the capillary viscometer coincide with the readings measured by the magnetoelastic viscometer (Fig. 2.17a, b). This fact proves that the test oil samples preserve the properties of the Newtonian fluid at the operating frequency < 30 kHz (at shear rate <10³ s⁻¹). Viscosity values of these oils measured by the solid-state viscometer are much lower than that obtained by the capillary and magnetoelastic viscometers. This confirms that the oils behave as

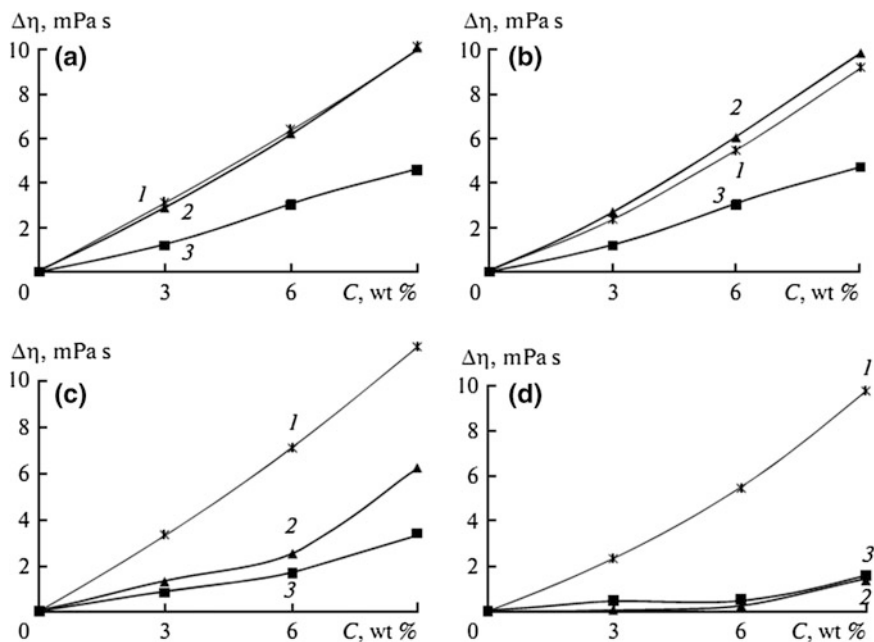


Fig. 2.17 Changes in the oil viscosity on the concentration of **a** PMMA-1, **b** PMMA-2, **c** PMMA-3, and **d** PMMA-4 modifiers with different molecular masses, introduced into the base oil PAO6 upon measuring by 1 capillary method, 2 magnetoelastic, and 3 solid-state viscometers

non-Newtonian fluids at the operating frequency (5.3 MHz) of the solid-state viscometer (at shear rate about 10^5 s^{-1}). It means that the oil PAO6 with polymer additives has a pseudoplastic behavior characterized by decreasing viscosity with increasing shear rate.

As the molecular weight of the additive increases (introduction of PMMA-3) the non-Newtonian behavior of the test oils is observed already at the operating frequency of the magnetoelastic viscometer (Fig. 2.17c). Further increase in the molecular weight of the additive (PMMA-4 VI) results in a situation when the apparent viscosities of the oils coincide at the frequencies 30 kHz and 5.3 MHz or are close to the base oil values without additives (Fig. 2.17d).

The analysis of correlations between the readings given by the magnetoelastic, capillary and solid-state acoustic viscometers for the tested base mineral and synthetic oils has indicated that the developed viscometer shows the data close to the capillary method within the range 17–500 cSt. The solid-state acoustic viscometer gives the least validity in measuring viscosity above 300 cSt. Its readings exceed considerably the anticipated data, evidently because the oil layer on its sensitive surface behaves like a gel at high operating frequency of the viscometer.

Monitoring of artificially aged mineral oil has revealed that the readings of the solid-state viscometer are much higher than viscosity measured by the magnetoelastic viscometer. This can result from the changes in chemical structure of the oil

during artificial aging, and intensified chemical activity leading to the change in the interfacial interactions between the oil and sensitive surface of the solid-state viscometer. Since the detector is sensitive to the properties in a very thin layer of the oil, evidently, these interfacial interactions affect the readings.

Investigations of the effect of PMMA VI improvers on the viscometer readings have indicated that with increasing molecular weight of PMMA under the same concentration in the synthetic base, the oil starts to behave like the non-Newtonian fluid at lower frequencies of viscosity measurements. As the molecular weight of the additive increases till $M_w = 530,537$ Daltons, the apparent oil viscosities measured at frequencies 30 kHz and 5.3 MHz coincide and approach the viscosity values of the base oil without additives. The results obtained agree well with the conclusions presented elsewhere [35]. They have proved that mineral oils behaving as Newtonian fluids under low velocities start to behave like non-Newtonian fluids under the shear rates above 10^5 – 10^6 s⁻¹ frequently occurring in practical applications.

Evidently, to make a correct choice of the lubricating oil with account of predicted rheological behavior in a tribosystem and its monitoring during operation, it is expedient to measure viscosity at the shear rates close to those used in the real tribosystems. In particular, it is important to estimate viscosity of non-Newtonian engine oils at medium shear rates (10^3 – 10^4 s⁻¹) at low temperature, and high shear rates (10^5 – 10^7 s⁻¹) at high temperature to make the best correlations with the engine performance [36].

2.6 Conclusions

An important aspect of ensuring the proper operation of tribosystems is the correct selection of oil, according to viscosity and its variation with temperature, as well as monitoring the oil viscosity during operation. If a change in viscosity is detected, subsequent analysis of the oil can identify the cause of such change. Either an increase or decrease in oil viscosity can result in the disturbance of the bearing capacity of tribosystem.

The review of methods of monitoring the oil viscosity shows that at present, portable viscometers requiring periodic sampling of oil are widely applied, however real-time monitoring is necessary for the reliable operation of machines. Among the devices mounted directly into the oil circulation lines and, particularly, into the lubrication systems of vehicles, acoustic devices are the most promising. Research centers carry out works for the perfection of methods for measuring the viscosity and the design of acoustic devices with the purpose of their wide application for real-time diagnostics.

In parallel with solid-state sensors based on acoustic waves, magnetoelastic viscosity sensors are currently under development; they operate at lower frequencies. Both piezoelectric and magnetoelastic types of the on-line acoustic viscometers have proved to be promising in the real-time monitoring of lubricating oils.

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