Procedures for measuring thickness of lubricating film using capacitive method on Amsler-type friction machines

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Abstract. A technique has been developed for measuring the thickness of a lubricating film by the capacitive method on Amsler-type friction machines. A diagram of the implementation of the original device for solving the problem is described, a method for its calibration is described. It was experimentally established that the applied method is highly stable in the results obtained in a wide range of measured values.

1. Introduction
Today, roller friction machines (II 5018, 2070 SMT-1, UMT, etc.) are widely used in tribological tests. At the same time, numerous test experts note the need for their modernization in order to increase the precision of measurements of the parameters of friction modes, as well as to meet the requirements of the latest standards [1-3].

Another vital feature is the choice of lubricant type, as its properties must meet the modern requirements for friction units [4]. Assessing of the operational properties of lubricants requires the knowledge of the lubricant film thickness in the contact zone.

An analysis of the designs of modern Amsler-type friction machines demonstrates that the industry does not make devices for quantitative assessment of lubrication conditions or for measuring film thickness in tribo-couplings. This requires numerous researchers to develop devices of original design.

Snegovsky F.P., Kodnir D.S., Reschikov V.F., Raiko M.V., GuzenkoM.Yu., Pavlik B.B. and others paid much attention to this issue. [5-8].

Their works concern mainly acoustic and electrical (electrical resistance and capacitive) methods of assessing lubrication conditions and measuring film thickness in couplings. This is because these methods have a number of advantages: simplicity of control, convenient data output from an analog-to-digital converter (ADC) to a personal computer (PC) and subsequent processing; low power consumption, small dimensions, etc.

Capacitive methods can be implemented, depending on the shape and size of the parts, in two different methods.

The first is based on the use of a sensor mounted in one of the contacting parts (for example, in tribological monitoring of a “roller-block” friction pair, it is a shaft). The sensor is isolated from the part and serves as a movable capacitor plate; the stationary plate is the opposite area of the second contacting part (the block). In this case, the lubricant is a dielectric.
The disadvantages of this method are nested in the limitations associated with ramming the capacitive sensor into the body of the sample, as well as with the difficulties when using the method on small or complex surfaces (for example, gear wheels, rolling bearings, etc.).

In the second method, contacting parts (the roller and the block) become the capacitor plates, while the lubricating layer acts as a dielectric.

The capacity of such a capacitor can be calculated as the capacity of the flat capacitor

\[ C = \frac{S \cdot \varepsilon \cdot \varepsilon_0}{d} \]

where \( S \) – area of the block, \( m^2 \);
\( \varepsilon_0 \) – dielectric constant;
\( \varepsilon \) – relative dielectric permeability of the lubricant;
\( d \) – lubricant film thickness, \( m \).

The main disadvantage of this method is the calibration of the sensor.

The authors have experimentally established that many of the proposed methods and original devices for capacitive measuring of the lubricant film thickness have a number of significant disadvantages, such as dispersion in readings, when measuring the lubricant film thickness for rotating roller, even under identical conditions.

2. Goals and objectives of the study

The goal of the paper is to develop an approach for measuring the lubricant film thickness on Amsler-type friction machines.

To achieve this goal, it is necessary to design an original device and a method for its calibration, validate the device, and introduce it into the daily tribological research.

3. Materials and methods of the study

If we include a flat capacitor in a divider (figure 1) and apply to the latter an alternating voltage of high frequency, then the divider’s voltage drop will change depending on capacity of the capacitor, i.e. depending on thickness of the lubricant film.

![Figure 1. Device for measuring the lubricant film thickness, a functional diagram](image)

The capacitive resistance of such a capacitor can be determined from the dependency

\[ x_C = \frac{1}{2 \cdot \pi \cdot f \cdot C} = \frac{d}{2 \cdot \pi \cdot f \cdot S \cdot \varepsilon \cdot \varepsilon_0} \] (1)
where \( f \) – current frequency, Hz.

Divider current

\[
I = \frac{U_{in}}{2 \cdot R + \frac{d}{2 \cdot \pi \cdot f \cdot S \cdot \varepsilon \cdot \varepsilon_0}}
\]  

(2)

where \( U_{in} \) - voltage at the divider input (see figure 1), V;

\( R \) – divider resistor resistance, Ohm.

Considering (1) and (2), it is possible to determine the voltage drop across the capacitance

\[
U_C = \frac{U_{in} \cdot d}{4 \cdot \pi \cdot R \cdot f \cdot S \cdot \varepsilon \cdot \varepsilon_0 + d}
\]  

(3)

Using simple transformations, we obtain the expression for lubricant film thickness from (3)

\[
d = \frac{4 \cdot \pi \cdot U_C \cdot R \cdot f \cdot S \cdot \varepsilon \cdot \varepsilon_0}{U_{in} - U_C}
\]  

(4)

A micro-controller with integrated 12-bit multichannel ADC is used to measure \( U_{in} \) and \( U_C \). After a full measurement cycle, filtering and averaging of the measured values using the floating-point unit (FPU) integrated in micro-controller, the lubricant film thickness is calculated according to the formula (4).

However, such a measurement approach is prone to the above-stated significant drawback: a significant dispersion in readings over time and small ranges of measurement of contacting film. This required an improvement in the design of the device.

Which was achieved by including into the device’s electrical circuit a digital controlled-amplitude generator implemented on a twisted-ring counter.

Functionally, the instrument consists of a measuring transducer and a power supply unit (figure 2).

![Figure 2](image)

**Figure 2.** Device for measuring the lubricant film thickness, a block diagram: \( MT \) – measuring transducer; \( PSU \) – power supply unit; \( PC \) – personal computer.

The measured capacitance is connected to one of the bridge arms (see figure 3); sinusoidal voltage is supplied from the generator “G” to the bridge’s upper point, and then to the synchronous detector “SD”. From the bridge, the voltage is fed to the repeaters “R”, from where it is supplied to the differential amplifier “DA” and then to the upper input of the “SD”.
Figure 3. Measuring transducer, a functional diagram: $G$ – generator; $DA$ – diode amplifier; $SD$ – synchronous detector; $R$ – repeaters.

At the output of the synchronous detector, the pulsating voltage is converted into a constant voltage using a filter (figure 4).

Figure 4. Synchronous detector operation

The device was tested on a modernized friction machine II 5018 [9].
The procedure for preparing for measurements includes the following steps:
- isolation of the roller (or the holder of the block), the loading mechanism, from the friction machine by placing a ring of dielectric material on the upper shaft;
- installation of current collectors of the upper and lower shafts, to improve the precision of measurements and to gauge the electrical signal from the upper and lower shafts;
- connecting to the ADC the device for measuring the lubricant film thickness (figure 2);
- connecting the ADC to a PC.
The new device was calibrated using polyethylene films of various thickness, with dielectric permeability close to that of lubricating oil.
The films were installed alternately between the test specimens, under a load that had insignificant impact on their deformation.
In this case, the dispersion in instrument readings stayed within ±5%.
The calibration curve is shown in figure 5.
Figure 5. Calibration curve of the device for measuring the lubricant film thickness.

4. Results
Experimental studies were carried out according to the “roller-block” scheme (the roller is made of “45 GOST 1050-2013” steel, the block is made of “BrAZh-9-4 GOST 18175-78” material). The block had a different diameter clearance, 15 and 30 µm [10].

Before the tests, the friction pairs had additional run-in. The roughness of the surfaces was determined using a surface analyser.

The results of measuring the lubricant film thickness were displayed on a computer screen as oscillograph recording. (figure 6, (a), (b)).

Figure 6. Oscillograph recording of lubricant film thickness in “roller-block” friction pair (steel “45” – “BrAZh 9-4”), V = 0.5 m s⁻¹, lubricant I-40A (flow rate 0.03125 min⁻¹) with diameter clearance:
a) 15 µm (Ra = 0.3 for the roller, = 0.8 for the block)
b) 30 µm (Ra = 0.3 for the roller, 0.7 for the block).
To reduce labour intensity and increase the data flow during the experiment, the test chamber was modernised.

Liquid lubricant “I-40A GOST 20799-88” was circulated into the friction zone using a proprietary-design system [9].

The temperature in the contact zone was determined using calibrated thermocouples.

The test results are presented in the table 1 and in figure 6.

| Diameter clearance, \( \delta, \mu m \) | Specific contact pressure, \( p, \text{MPa} \) | Average value of the instrument readings for measuring the lubricant film thickness, \( U, V \) | Lubricant film thickness, \( h, \mu m \) |
|-----------------------------------------|---------------------------------|-------------------------------------------------|----------------------------------|
| 15                                      | 2.5                             | 0.270                                           | 2.92                             |
| 5                                       | 0.250                           |                                                  | 2.52                             |
| 7.5                                     | 0.240                           |                                                  | 2.34                             |
| 10                                      | 0.234                           |                                                  | 2.24                             |
| 12.5                                    | 0.229                           |                                                  | 2.16                             |
| 15                                      | 0.223                           |                                                  | 2.07                             |
| 20                                      | 0.210                           |                                                  | 1.88                             |
| 25                                      | 0.180                           |                                                  | 1.51                             |
| 30                                      | 2.5                             | 0.282                                           | 3.19                             |
| 5                                       | 0.257                           |                                                  | 2.65                             |
| 7.5                                     | 0.238                           |                                                  | 2.31                             |
| 10                                      | 0.230                           |                                                  | 2.17                             |
| 12.5                                    | 0.218                           |                                                  | 1.99                             |
| 15                                      | 0.212                           |                                                  | 1.91                             |
| 20                                      | 0.172                           |                                                  | 1.42                             |
| 25                                      | 0.110                           |                                                  | 1.04                             |
5. Discussion
Experimental studies have shown that the proposed approach for measuring the lubricant film thickness allows obtaining stable readings under identical test conditions, with a dispersion of ±5% and minimum thickness of a lubricating film from 1 μm (see the table).

It was found that at low roller rotation speeds (V = 0.5 m s⁻¹) and high specific pressures, the lubricant film thickness is higher in a friction pair with 15 μm diameter clearance compared to 30 μm diameter clearance.

6. Summary
1 An original device for measuring the lubricant film thickness has been developed, tested and introduced into the practice of tribological research. Its principle of operation is based on the capacitive method using a generator implemented on a twisted-ring counter.

2 The paper presents the method of calibration of a device for measuring the lubricant film thickness, based on the use of films of various thickness, with dielectric permeability close to that of lubricating oil.

3 It was found that the proposed device ensures obtaining stable results with a dispersion of ±5%, allowing for measurements of the thickness of contacting film starting from 1 μm.

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