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A NEW EHD PHENOMENON: THE RHEOLOGIC HYSTERESIS

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Abstract. The film thickness and traction of the elastohydrodynamic lubrication (EHL) regime were measured on a two disk (SAE) rig. The two parameters present larger values at the increase of the loading compared with the unloading. This phenomenon was called "rheological hysteresis" (RH) and is described in the present paper. For a better presentation of the RH phenomenon, the SKF film percent was substituted with a new notion: contact percent (C%). Also, there are introduced some new notions: absolute rheological deflection (RD), relative rheological deflection (Δ_{RD}), absolute area of the hysteresis loop (A_L) and relative area of the hysteresis loop (Δ_{AL}). The rheological hysteresis appears both at the film thickness and traction measurements.

Key Words: rheologic hysteresis, elastohydrodinamic lubrication, Hertzian line contact.

1. INTRODUCTION

The first authors who observed and studied the elastohydrodynamic (EHD) lubrication regime were Ertel, Grubin, Dowson and Higginson [1].

The elastohydrodynamic (EHD) lubrication, as the mainframe of the present paper, was studied by several authors (only partially quoted further on) and specially in these main aspects:

- the theory of the EHD regime [1-3]; the rheological effect of the viscosity variation with temperature and pressure in the contact zone [3-8];
- the theory of liquid-solid lubrication in EHD regime [1-6];
- the EHD film thickness [1, 4, 6-11];
- traction in EHL regime [7, 15-12];
- the measurement technique of the lubricant film response to pressure, velocity, temperature in the EHD regime [1, 4, 6-13].

The two main parameters of the EHL regime (film thickness and traction) depend on several factors: oil properties, surface roughness, materials, speed, load etc. Until now, all these influences were studied <u>only while loading</u>. This paper presents some interesting results observed during a complete <u>cycle of loading and unloading</u>, similar to the real functioning.

The major result of the research consists in the observation of a phenomenon called "rheological hysteresis" that occurred during the loading-unloading cycle.

2. THEORETICAL ASPECTS PRESENTED BY VARIOUS AUTHORS

Several authors agreed that, while passing through the contact zone, the film thickness and rheology of the lubricant depend specially on pressure and temperature. The passing time through contact is very short ($10^{-4} – 10^{-6}$s) with a state change of the lubricant (from liquid to solid and back to liquid) [1-6].

At the classical pressure distribution in the contact zone, a pressure spike is added, that strains the zone towards its exit, so that the film thickness becomes $h_0 \approx 0.8 \cdot h$ [1, 4-7].

Recommended by Radu P.VOINEA, member of the Romanian Academy

The researches carried out by SKF (1968) and by other authors [1, 4, 8, 11] stated that roughness influences the EHD regime, its total or partial presence. So, now it is generally accepted that the SKF diagram shows the variation of the film percent versus the film parameter ($x_h = \frac{h}{\sqrt{R_{a1}^2 + R_{a2}^2}}$ or, $x_h = \frac{h}{R_z}$ [1]). Later this curve was displaced towards left consequently to the measurements made on several gear line contacts [8].

3. THE EXPERIMENTAL INSTALATION

Several papers presented various possibilities and testing rigs for the measurement of the film thickness and of the corresponding EHD regime. It is interesting to remark that for measuring the oil viscosity variation with the pressure, initially were used rollers functioning at pressures of 0.8-1.2 GPa [1, 3-11], than plane contacts and, lately, line contacts (two or four disk rigs) [1-3, 9-11].

The experimental results used in this paper were measured on a complex two-disk installation (see Appendix) with an electrical resistance device for film thickness measurement, presented in [11]. The rig allows the variation of several parameters: load, rolling speed, rolling and sliding speed, temperature. The parameters measured are the film percent and the friction coefficient and the results can be observed directly on an oscilloscope, read on a digital multimeter, recorded on paper by an oscillograph or stored electronically by a data acquisition device. Also, the results can be presented as instant values or as mean values on a desired period, using a time integrator device.

The contact load was varied step by step during the loading-unloading cycle.

We stress that the measurements were made very carefully in order to obtain an error margin less than 2%.

The experimental results presented in this paper were obtained on disks with low thickness in order to obtain a film percent larger than 70% that indicates an acceptable or full EHD regime and only for the pure rolling case.

4. NEW EXPERIMENTAL RESULTS AND INTERPRETATIONS

The measurements were made by increasing the load (loading) step by step, up to a maximum value (corresponding to $P_{H,max}$ = 1.2 GPa), followed by the decreasing of the load (unloading), at the same steps, down to zero and, also, for various values of speed (between 9 m/s to 35 m/s) and temperature (ranging from 40 to 90 ^{O}C).

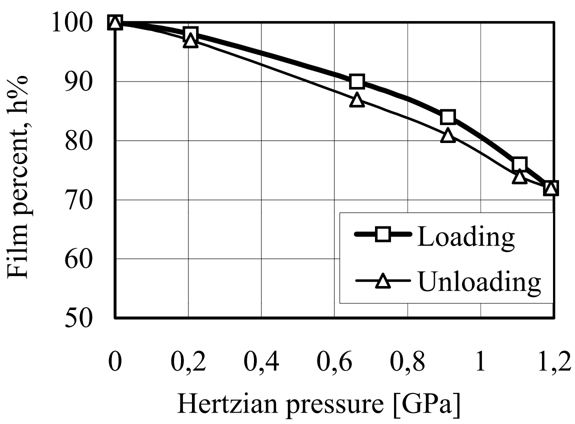


Figure 1. Load influence on film percent

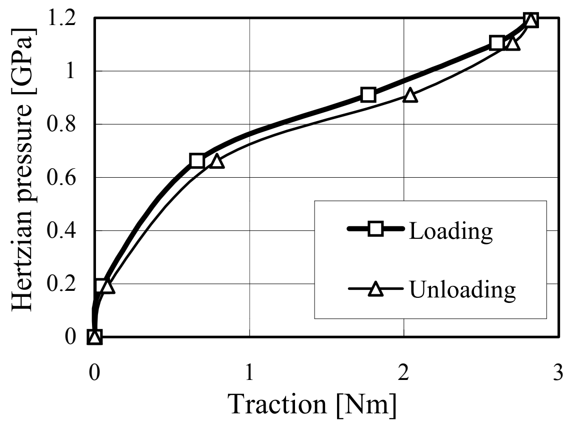


Figure 2. Load influence on traction

The film thickness measured on the installation presents a rheological phenomenon of hysteresis loop during the process of uploadig followed by downloading. We name this phenomenon "*rheological hysteresis*" (RH) and it is presented in figure 1 as a SKF type diagram.

The traction measured on the installation presents also a rheologic phenomenon of hysteresis loop during a complete loading cycle (loading – unloading) and it is presented in figure 2.

The diagrams in figure 1 and 2 which are plotted for the rolling speed v_r = 11.2 m/s and the contact outlet temperature T = 50 OC.

4.1. For the film thickness, we propose to change the presentation from this classical SKF form (in figure 1) to the one in figure 3.

This change allows a better presentation of the observed RH phenomenon by replacing film percent (h%) with the term contact percent, C%, defined as:

$$C\% = \left(1 - \frac{h\%}{100}\right) \cdot 100 \tag{1}$$

Figure 4 shows a better presentation of the RH aspect by reversing the axes.

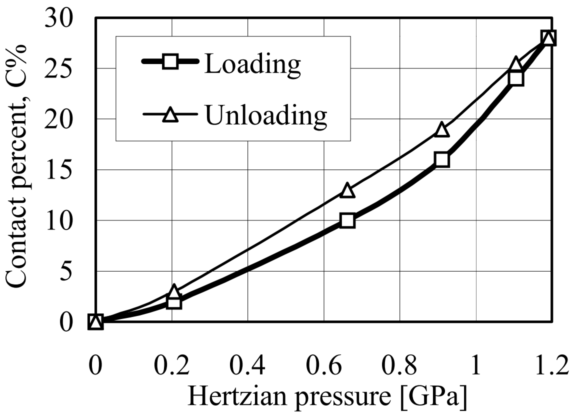


Figure 3. Load influence on film contact

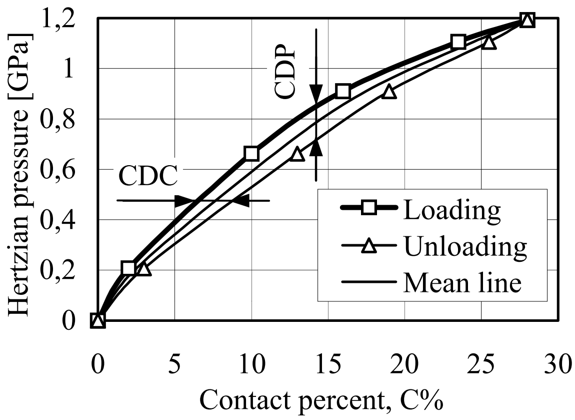


Figure 4. Load influence on film contact (reversed axes)

4.2. The authors present a new parameter: absolute rheological contact deflection, CD and, respectively, relative rheological contact deflection, Δ_{CD}. This new parameter is used for measuring the variations of the contact hysteresis.

The contact deflection can be measured in two directions:

- along the pressure axis results the absolute and the relative contact deflection related to pressure CDP and Δ_{CDP};
- along the contact axis results the absolute and the relative contact deflection related to contact percent CDC and Δ_{CDC}.

These deflections are defined as:

$$\Delta_{CDP} = \frac{CDP}{P_{H,\max}} \tag{2}$$

$$\Delta_{CDC} = \frac{CDC}{C\%_{\max}} \tag{3}$$

where $P_{H,max}$ is the maximum Hertzian pressure, in this case $P_{H,max}$ = 1.2 GPa (figure 4) and C_{max} is the maximum contact percent (corresponding to the maximum pressure $P_{H,max}$) for the hysteresis loop.

The total absolute and relative rheological contact deflection, CD and Δ_{CD}, are computed on the mean line, measuring the absolute deflections on both axes in the same point, using:

$$CD = \sqrt{CDP^2 + CDC^2} \quad \text{and} \tag{4}$$

$$\Delta_{CD} = \sqrt{\left(\frac{CDP}{P_{H,\max}}\right)^2 + \left(\frac{CDC}{C\%_{\max}}\right)^2} \tag{5}$$

where $C\%_{max}$ is the maximum contact percent corresponding to the maximum Hertzian pressure $P_{H,\ max}$.

4.3. The diagram that shows the traction variation with the Hertzian pressure is presented in figure 5. It can be seen also the hysteresis form for a complete load cycle. It can be seen that the traction loop area is smaller than the similar one for the film thickness.

4.4. For the traction we define the similar parameters: absolute rheological traction deflection, TD and, respectively, relative rheological traction deflection, Δ_{TD} (figure 5).

Related to the two axes there are:

- the absolute and the relative traction deflection related to pressure TDP and Δ_{TDP};
- the absolute and the relative traction deflection related to traction TDT and Δ_{TDT}.

These deflections are defined by:

$$\Delta_{TDP} = \frac{TDP}{P_{H,\max}} \tag{6}$$

$$\Delta_{TDT} = \frac{TDT}{T_{\max}} \tag{7}$$

$$TD = \sqrt{TDP^2 + TDT^2} \quad \text{and} \tag{8}$$

$$\Delta_{TD} = \sqrt{\left(\frac{TDP}{P_{H,\max}}\right)^2 + \left(\frac{TDT}{T_{\max}}\right)^2} \tag{9}$$

where T_{max} is the maximum traction corresponding to the maximum Hertzian pressure $P_{H,\ max}$.

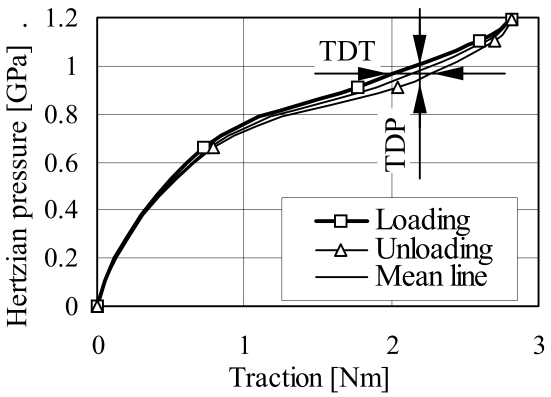


Figure 5. Load influence on traction (v_r=26.8 m/s; T=50° C)

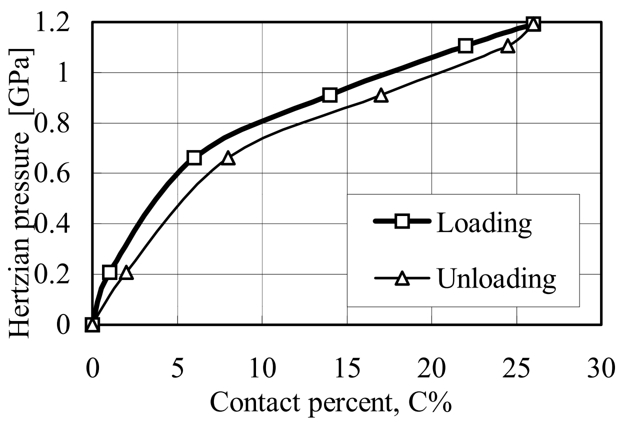


Figure 6 (T = 50° C)

4.4. For the contact percent we present another new parameter: aria of the contact hysteresis loop, A_{CL}, respective, relative aria of the contact hysteresis loop, Δ_{ACL}.

$$A_{CL} = \int_0^{P_{H,\max}} f_{CL}(p)dp - \int_0^{P_{H,\max}} f_{CU}(p)dp \tag{10}$$

$$\Delta_{ACL} = \frac{A_{CL}}{\int_0^{p_{H,\max}} f_{Cm}(p)dp} \cdot 100\,\% \tag{11}$$

where f_{CL} and f_{CU} are the functions that estimate the contact percent variation with pressure at loading and, respectively, at unloading and f_{Cm} is the function that estimates the mean contact variation with pressure.

4.5. For the traction we present the similar parameter: aria of the traction hysteresis loop, A_{TL}, respective, relative aria of the traction hysteresis loop, Δ_{ATL}.

$$A_{TL} = \int_0^{p_{H,\max}} f_{TL}(p)dp - \int_0^{p_{H,\max}} f_{TU}(p)dp \tag{12}$$

$$\Delta_{ATL} = \frac{A_{TL}}{\int_0^{p_{H,\max}} f_{Tm}(p)dp} \cdot 100\,\% \tag{13}$$

where f_{TL}, f_{TU} and f_{Tm} are the functions that estimate the traction variation with the loading, unloading and mean pressure.

4.6. Figures 4, 6, 7 and 8 show the contact percent variation with Hertzian pressure and plotted for the rolling speeds from the Table 1.

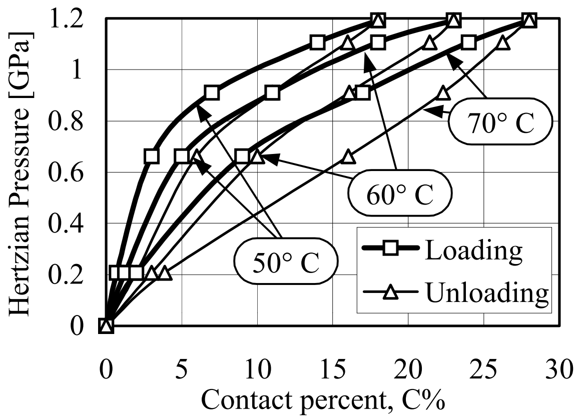


Figure 7

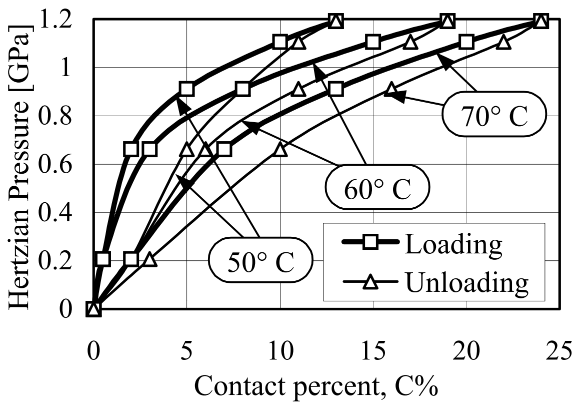


Figure 8

Table 1

Figure	4	6	7	8
Rolling speed, v_r [m/s]	11.5	22	26.8	31

In all these figures the RH phenomenon can be clearly observed and it depends on temperature and rolling speed.

The measurements were made by increasing the load (upload) step by step, up to a maximum value (corresponding to $P_{H,max} = P_1 = 1.2$ GPa), followed by the decreasing of the load (download), at the same steps, down to zero. Also, the experiments were made for various values of speed (between 9 m/s to 35 m/s) and temperature (ranging from 40 to 90 ^{O}C).

Observations:

• The rolling speed has a non-linear influence on RH: at medium speeds RH is larger than at low or high rolling speeds.

• The contact percent decreases with the speed increase as seen in the figures 3, 4 and 7 where are plotted the curves for the same temperature (50°C), but for various speeds.

• The temperature has a direct influence on HR, but also influences the contact percent and, through it, the temperature seems to have also an indirect influence on HR.

• The temperature increase leads to a contact percent increasing (film percent decreasing) as shown in figures 6 and 7 which are plotted for the same rolling speed vr = 26.8 m/s and vr = 31 m/s, respectively, but for three different temperatures (50°C, 60°C and 70°C).

4.7. Figures 9 and 10 present the traction variation the variation of the traction and its rheologic hysteresis loop for three different temperature values.

Both figures present similar behavior of the rheologic hysteresis.

Observations:

• temperature rise, up to a certain limit, leads to an improvement of the rheologic behavior of the EHD lubrication regime; • the differences between the measured values of loading versus unloading are larger at larger values of the Hertzian pressure; • speed increasing seems to reduce the rheologic hysteresis, but this behavior can, for the time being, be appreciated only qualitatively. A quantitative appreciation cannot be made yet.

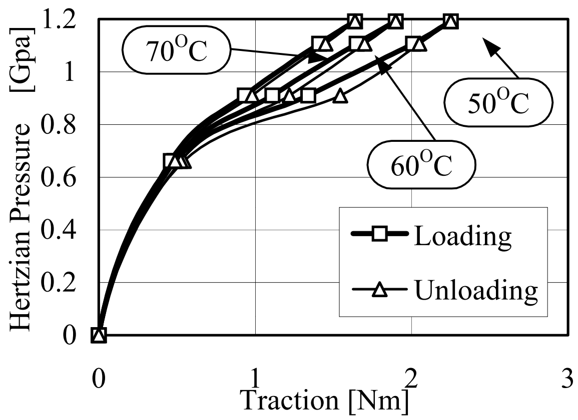


Figure 9 Traction variation at 26.8 m/s

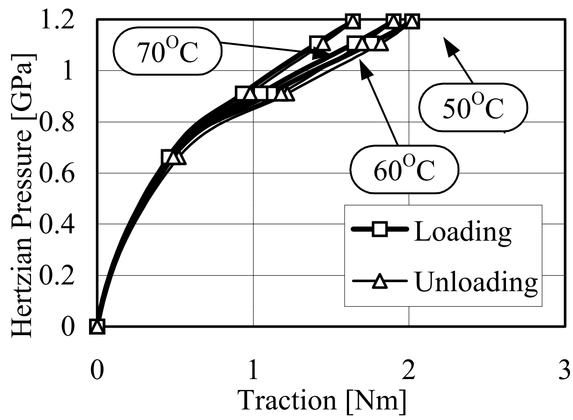


Figure 10 Traction variation at 31 m/s

The rheologic behavior, the presence and variation of the rheologic hysteresis loop can be easily being observed from all the figures presented, but they cannot be quantified for a proper analysis.

5. PHENOMENON EXPLANATION

5.1. One explanation for the observed phenomenon will take into account the sonicity theory. The S.A.E. installation with EHD fluid film can be compared with an energy accumulation by compression in fluids, imagined originally by the Romanian scientist George Constantinescu. He was the first to demonstrate and to use water and oil compressibility [14], presented in his sonicity theory.

In our case, the rheological hysteresis effect can be explained by the accumulation of the energy in the fluid film, periodically, but in a very short time (about 10^{-5} – 10^{-6} s). The energy dispersion appears at the pressure reduction (during download), with a certain delay due to the rheological inertia.

5.2. Another explanation of this behavior must take into account the thermal problem in the contact. For a proper evaluation (both qualitative and quantitative) of this rheological phenomenon it must be considered the way the heat is generated in the contact, at loading, and its dissipation speed while unloading.

6. CONCLUSIONS

A complex SAE equipment was used for the line film thickness study and, for the first time, several phenomena were observed.

• The film thickness and traction behavior was studied on a complete loading-unloading cycle.

• A hysteresis type phenomenon, we called rheological hysteresis, appears only in the full EHD lubricant film. This phenomenon is similar with the hysteresis loop of elastic materials with inner friction or with the one of some electric circuits.

• For an easier study of this phenomenon, a new representation was proposed: contact percent–load diagram.

• Also there were defined the rheological hysteresis parameters: *hysteresis loop area* and *rheologic deflection*. In a second paper the authors propose to analyze the variation of the parameters of the rheologic hysteresis. Their behavior will be studied related to various factors: load, speed and temperature.

It results that for the first time, using the film thickness and traction measurement installation for line contact, the presence of this rheological hysteresis phenomenon showed that in the zone of the Hertzian contact, at high pressure (1.2 GPa) and in very short passing times (around 2·10-6s) [2,3,5], the lubricant transforms itself, from a newtonian fluid, in a quasi-solid with elasto-plastic properties similar to elastomers.

We consider this an interesting approach and also an easy way to study the rheological behavior of the fluids and we suggest to other researchers to follow it.

The authors would be grateful for any suggestions and shared experience.

APPENDIX

The two disk experimental rig is composed of two parts:

- the electric, hydraulic, and mechanical experimental part destined to obtain the EHL line contact and equipped with the facilities necessary for the variation of the main parameters of the EHL regime;
- the electronic measurement part composed of several electric devices in order to display and record the measured parameter.

The whole installation and the measurement technology are presented in [11]. The rig allows the variation of several parameters: load, rolling speed, rolling and sliding speed, temperature.

Figure A.1 presents the cinematic scheme of the testing rig, where: 1 – electric engine; 2 – belt transmission; 3 – gear box; 4′, 4″, 5′ and 5″ - shafts; C – coupling; 6 – loading device; 7 – disk box; 8 – temperature measuring device; 9 – pumping, filtering and thermostat device D_1 – upper disk; D_2 – lower disk. The belt transmission (2) allows 9 speeds of the shafts. The gear box (3) permits the rotation of the shaft with the upper disk with different speeds in order to obtain pure rolling speed or rolling and sliding speed.

The loading device (6) is mechanical and allows loading and unloading with the necessary force. The temperature device (9) measures temperature both at the inlet and at the outlet zones of the contact. The disks are electrically insulated from the rest of the rig.

The parameters measured are the film percent and the friction torque that takes place between the two disks (D1 and D2).

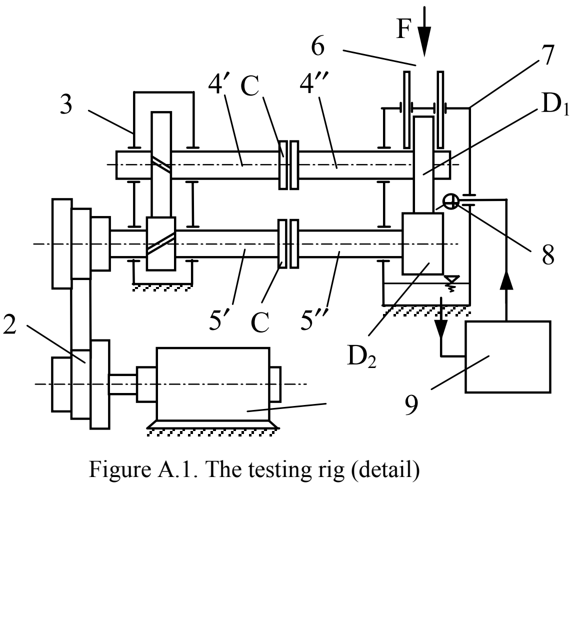


Figure A.1. The testing rig (detail)

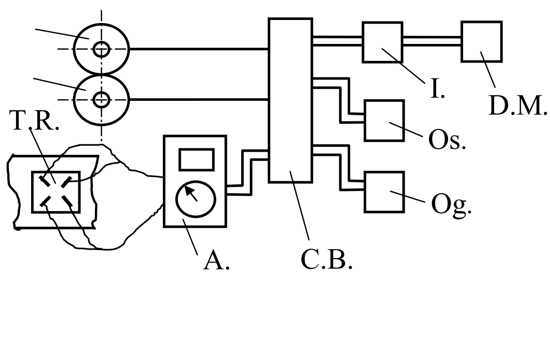
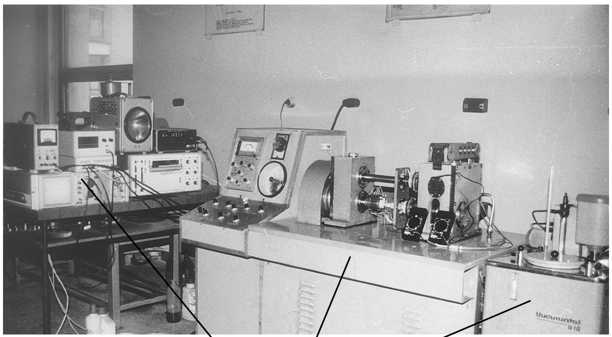


Figure A.2. The electrical measurement device

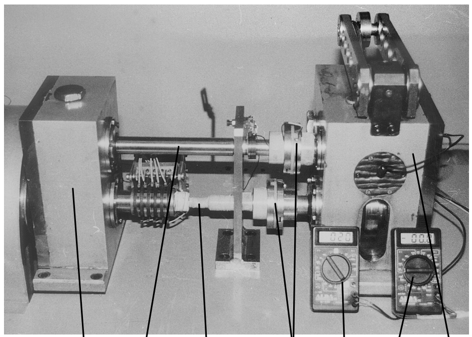
Figure A.2 shows the electrical devices mounting. The results can be observed directly on an oscilloscope (Os), read on a digital multimeter (D.M.), recorded on paper by an oscillograph (Og.) or stored electronically by a data acquisition device, all these connected with a connecting box (C.B.).

Also, the results can be presented as instant values or as mean values on a desired period, using a time integrator device (I.).

The friction that takes place between the two disks will generate an angular deformation of the shafts that is transformed in an electrical signal by the tensometric resistances (T.R.).



Picture 1



Picture 2

In Picture 1 the annotations are: 1 – the electronic measurement apparatus; 2 – the testing rig; 3 – the oil acclimatization device.

In Picture 2: 1 – the gear box; 2 – the upper shaft; 3 – the lower shaft (with the tensometric resistances); 4 – Oldham couplings; 5 – the temperature measurement device #1 (for the enter in the contact); 6 – the temperature measurement device #2 (for the exit from the contact); 7 – the disk box.

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