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Review

Electrical Methods for the Evaluation of Lubrication in Elastohydrodynamic Contacts

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This paper reviews the electrical methods to evaluate lubrication, with the focus on elastohydrodynamic applications. The methods are based on the measurement of the electrical resistance and/or capacitance, and are used to determine the thickness of lubricating films as well as to detect asperity contact in the mixed lubrication regime. The experimental works are introduced in which these methods are used in conventional sliding and rolling/sliding tests and machine component tests including piston ring and cylinder liner, cam and follower, and gears. Also some works on the effect of electric field upon lubrication phenomena are introduced. Advantages and disadvantages of the electrical methods are discussed.

Keywords: elastohydrodynamic lubrication, film thickness, measurement, electrical resistance, capacitance

1. Overview

The elastohydrodynamic (EHD) lubrication regime occurs in many machine elements, where a combination of geometrically converging surfaces, elastic deformations and variation of lubricant's viscosity with pressure, allow the formation a continuous lubricant film at extremely large pressures. These conditions are characteristic to rolling element bearings, gears, cams, the elements of toroidal continuously variable transmissions and constant velocity joints. Typically these contacts have dimensions less than one millimeter, which under load give rise to pressures of up to 3 GPa. The lubricant film, typically between one hundred nanometers and one micron thick, passes through the conjunction in about one millisecond. These extreme conditions make difficult the study of film formation and measurement of various parameters of the lubricant inside the contact.

The most widely used method nowadays, for studying the thickness of the EHD film employs the optical interferometry phenomenon [1,2]. This method was developed in the early sixties, and has been used to study the contact formed between a flat, transparent disc loaded against a shiny steel ball or roller. The contacting flat disc is coated with a semi-reflective layer, usually chromium, such that any incident light shone onto the contact, usually monochromatic, is twice reflected, firstly at the glass-metal layer interface and secondly at the ball or roller surface. Upon recombination the path difference between the reflected rays results in a series of bright and dark fringes due to either constructive or destructive interference of light. The addition of a solid spacer layer on top of the semi-reflective chromium layer usually made out of silica increases the separation between the solid surfaces of the contact allowing measurements of films theoretically as thin as a few nanometers [3]. The optical interferometry method allows precise measurement of EHD film thickness and the mapping of the whole contact area, making it a powerful technique for the study of mixed lubrication regime [4] or non-steady state events [5,6]. The main disadvantage of the optical interferometry is the fact that one of the contacting bodies must be transparent, which makes it impossible to adapt to the direct study of real machine components.

This limitation is not characteristic to the other group of methods used for the study of lubricated contacts namely the electrical methods. Historically, electrical methods such as voltage discharge, resistive, capacitive and inductive have preceded the optical methods for studying film formation in lubricated contacts. The main advantage of electric methods is the fact that the elastohydrodynamic contact is formed between two bodies made out of steel, which is identical to the contacts found in the machine components that work in the elastohydrodynamic regime. They also can be used to evaluate directly the lubrication in real machine components. There are, however, some disadvantages to the electrical methods too: the resistance and capacitance of the contact depend of the shape of the bodies, which can only be presumed inside the contact, where large local deformations occur; they are very sensitive to the purity of the lubricant and difficult to calibrate. Additionally these methods usually only give average values and offer no indication of the local shape of the film over the whole contact area. It has to be mentioned that the shape of the EHD film along the main rolling direction of the contacts and the pressure can be evaluated by using a thin metallic film deposited on the surface as one of the electrodes of a capacitor.

Usually electrical methods have been used to investigate lubrication phenomena in three directions: a) measurement of the thickness of the lubricant film, b) detection of full-film conditions and of asperity contacts in rough surfaces, c) evaluation of the performance of the lubricated contact under the effect of an electric field. This paper contains a review of the application of electrical methods to experimental studies on lubrication phenomena.

2. Measurement of lubricant film thickness

The problem of the lubrication mechanisms of gears and rollers was a subject of intense debate among the researchers and scientists throughout the first half of the twenty's century. This debate spun around theoretical work by Martin [7], who considered the contacting bodies rigid and the viscosity of the lubricant independent of the pressure, to develop a relationship for the oil film thickness based on the hydrodynamic theory. About three decades later, in a semi-analytical solution of exquisite elegance and simplicity, Grubin and Vinogradova [8] took in consideration both the elastic deformation of the contacting surfaces and a exponential variation of the lubricant's viscosity with pressure. They predicted a lubricant film bordered by parallel surfaces and of a thickness depending on the mechanical properties of the solid bodies in contact, the rheological properties of the lubricant and on the working parameters, i.e. entrainment speed and load. These theories needed experimental validation and electrical methods were first to be used.

Experiments carried out by Siripongse et al. [9,10], voltage discharge, and Crook [11], electrical resistance have shown that a continuous lubricant film can form even in the conditions of extremely large pressures generated in nominally line and point contacts. Siripongse and co-workers focused their study on the relation between the voltage/current characteristics and film thickness in line contacts [9] and point contacts [10]. The calibration of their technique was the main obstacle for getting reliable results, as the content and size of impurities in the oil changed significantly the slope of the breakdown voltage/film thickness dependence. They concluded that the variation of breakdown voltage with film thickness was linear, while the variations of speed or load had little or no effect on this. They also reached the conclusion that the standard concepts of hydrodynamic lubrication and elasticity, alongside with variation of the viscosity with pressure could alone explain the behavior of the lubricant in heavily loaded contacts.

In a series of papers intended to elucidate the mechanisms of lubrication of concentrated contacts Crook [11] evaluated the lubricant film thickness formed between lubricated discs, with parallel axes, by a capacitance method.

In order to avoid the incertitude introduced by the true shape of the deformed contacting surfaces and by the variation of the dielectric constant of the oil with pressure, he measured the capacitance between the discs and stationary, unloaded pads. A schematic of the disc apparatus is shown in Fig. 1. The calibration equation, which relates the capacitance of the pads to the film thickness, in case of undeformed discs, is given by the relation:

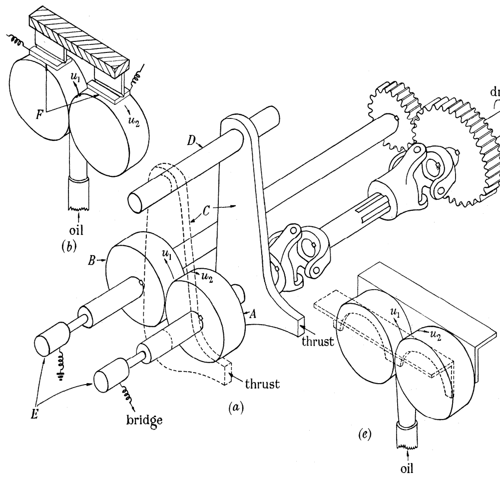

Fig. 1 Crook's disk machine (Ref. 11, Copyright The Royal Society. Used with Permission)

$$C_D = 2.38\left(h_{0D}^*\right)^{-\frac{1}{2}} \tag{1}$$

where h_{0D}^* is the minimum separation between discs. Figure 2 shows a comparison of the calibration curves obtained, in similar conditions, with Equation (1) and the more accurate relation by Dyson et al. [12]. Crook's results showed that, at low loads, the film thickness was proportional to the speed and inversely proportional to

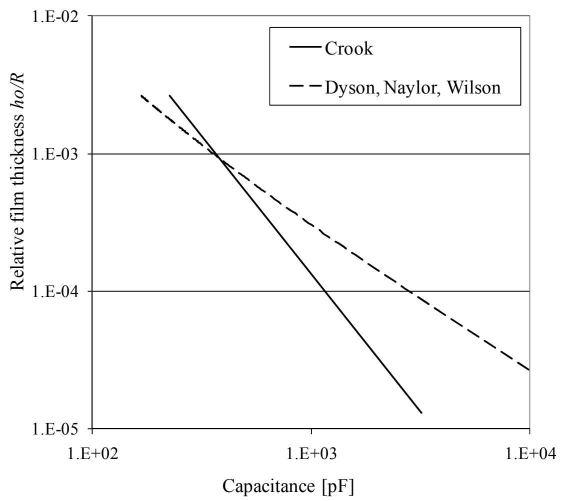

Fig. 2 Calibration curves for film thickness versus capacitance

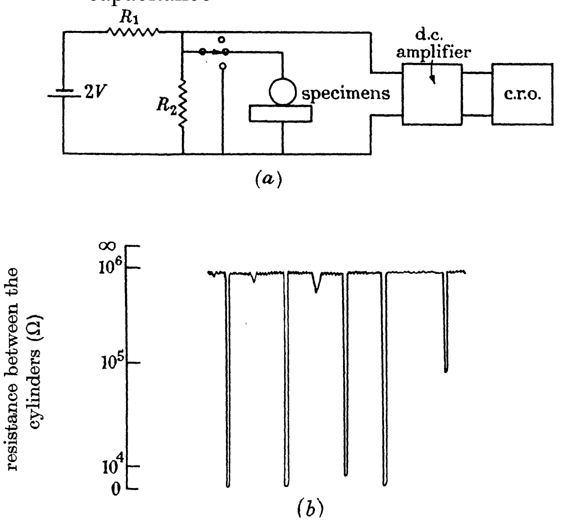

Fig. 3 Electrical resistance measurement by Archard and Kirk, (a) circuit, and (b) typical pattern of the recorded signal (Ref. 13, Copyright The Royal Society. Used with permission)

the load, as predicted by Martin's equation, but the absolute value detected was half of the theoretical value. At large loads however, the measured film thickness exceeded the calculated values. Crook also stated the importance of the variation of the viscosity with pressure and of the elastic deformation of the surfaces.

Further experimental evidence was given by Archard and Kirk [13] who measured both the resistance and the capacitance of the contact between cross axes cylinders. The schematic of the electrical circuit of their apparatus is shown in Fig. 3. They showed that the electric resistance of the contact indicated a film thickness far greater than that corresponding to the thickness calculated by the hydrodynamic theory for rigid surfaces and iso-viscous lubricant. The results indicated the existence of a hydrodynamic film at loads which were capable of causing plastic deformation to the hardened steel specimens. Measurement of the capacitance of the contact over a wide range of loads, velocities of the surfaces and viscosity of the lubricant led them to the conclusion that the elastohydrodynamic film thickness was proportional to the viscosity, surfaces velocity and radius of the contacting surfaces according to the relation:

$$h \propto (\alpha\eta)^{0.57} V^{0.55} R^{0.62} \qquad (2)$$

Refinements to the capacitive method, which involved one of the electrodes to be a sub-surface thin metallic foil, allowed the evaluation of the shape of the film in the rolling direction. Crook [14] using a chromium thin film gauge has been able to measure both the film thickness and the longitudinal shape of the film in a linear contact. Hamilton and Moore [15] use gauges of different materials able to measure either pressure and shape (manganin) or temperature and shape (nickel) of the EHD film, in a linear contact. They replace the steel central disc of a four-disc machine with a glass one, which has the transducer deposited on the periphery. The output voltage signal which reveals the variation of the capacitance of the contact as the gauge passes through the conjunction is collected by an oscilloscope. A similar method has been employed by Bartz and Ehlert [16] who measured pressure, temperature and film thickness in a two-disc machine. The capacitance used of measuring the film thickness was calibrated by introducing known capacitors into the circuit. They conclude that the effect of the pressure/viscosity coefficient upon film thickness is stronger than that of the inlet viscosity.

Apart from fundamental studies on the lubrication of rollers electrical methods have been used to estimate the film thickness in systems where optical interferometry is impracticable, such as gears, cam/tappet, the contact between piston ring/cylinder of internal combustion engines and plain hydrodynamic bearings.

MacConochie and Cameron [17] started from the premise that electrical resistance could not yield quantitative measurements of the elastohydrodynamic film thickness, used the discharge voltage to measure the thickness of the lubricant film formed between straight spur gears' teeth. The electric circuit employed was quite simple, using a cathode-ray oscilloscope to detect the discharge voltage for a certain pair of teeth, detected by a magnetic marker. A constant current was obtained by connecting a battery with a variable resistance. They studied the effect of load and oil viscosity on the film thickness variation on different points of the meshing cycle. The results showed a considerable thick film at the pitch line, but also that the film thickness varied little with the viscosity of the oil and rather more strongly with the load. Later, Ibrahim and Cameron [18] used the same experimental arrangement to study the scuffing phenomena in gears.

Similar to gears, cam/tappet mechanisms' contacts are characterized by large variations of load, velocity and geometry. This makes impossible their investigation with optical methods. On the other hand, electrical resistance and capacitance of the contact have been quite intensively used by various researchers to evaluate the lubricant film thickness in such systems. Vichard [19] made a comprehensive study of the transient elastohydrodynamic lubrication involving both entrainment and squeeze, with application to cam/tappet mechanisms. He used the capacitive method in his experimental validation of the theoretical approach. The correlation between measured capacitance and the film thickness was made on the basis of a theoretical analysis by Dyson and co-workers [12]. Van Leeuwen et al. [20] also studied the cam/follower lubrication in a specially designed experimental set-up which employed the resistance to detect full film conditions and capacitance measurements to estimate the film thickness, while the local temperature in the contact was detected with sub-surface transducers. To measure the capacitance they used a modified SKF Lubcheck instrument. For their testing conditions and lubricant a film thickness variation between 0.8 and 1.8 micrometers was detected, as shown in Fig. 4.

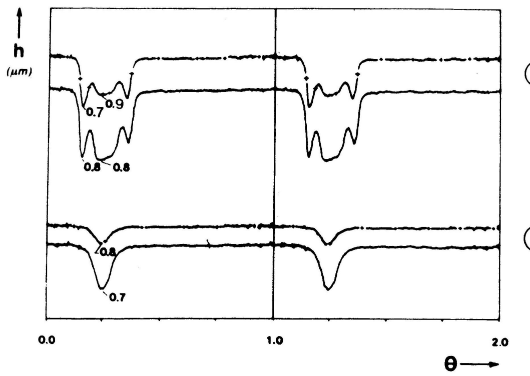

Fig. 4 Film thickness in a cam/follower contact (Ref. 20, Copyright Elsevier. Used with permission)

A great deal of research effort was put into the measurement of the lubricant film thickness in the contact between the piston ring and cylinder liner of internal combustion engines. The piston-ring cylinder-liner contact may experience various regimes of lubrication, i.e. hydrodynamic, mixed and boundary, but there is evidence that in some conditions the regime is elastohydrodynamic. As cited by Dowson et al. [21] Aue was the first to suggest that large enough pressures to generate elastic deformations of the cylinder liner and the barrel-shape of the ring create conditions for a full elastohydrodynamic film to form. Dowson and co-workers conducted their own investigation into this subject and their findings fully support this point of view. For this reason measurements of lubricant film thickness between piston-ring and cylinder are also included in this paper.

Furuhama and Sumi [22] used comparatively two methods to evaluate oil film thickness of the piston-ring. One was to measure the electric resistance/capacitance between the cylinder and the piston ring. The other was the measurement of the circumferential displacement of the gap of the ring. They concluded that estimation of the film thickness by direct measurement of the electric resistance and capacitance between the cylinder and ring was very difficult due to metallic contacts between these components. The second method allowed the authors to successfully evaluate the film thickness the results showing minimum film thickness at TDC and BDC and maximum at mid stroke. They also showed that the film thickness was proportional to the ratio $\mu U/W$, where μ is the viscosity of the oil, U is the speed and W the load. Hamilton and Moore [23,24] overcame the difficulties mentioned before, in using capacitance measurements to evaluate the film thickness between piston ring and cylinder, by employing a flat capacitive probe of a very small diameter, 1.25 mm in diameter, as seen in Fig. 5.

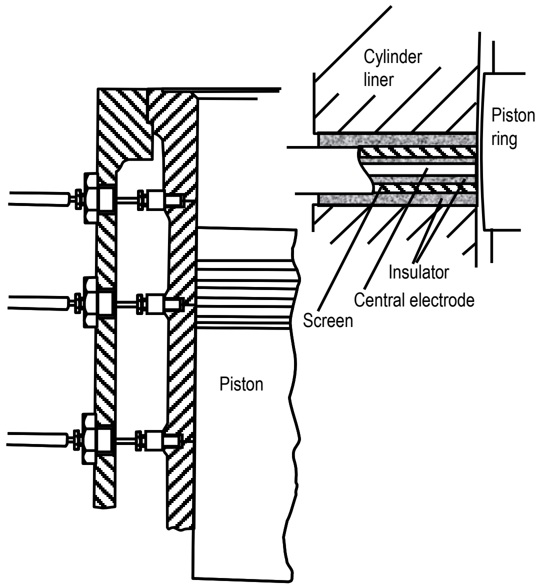

Fig. 5 Arrangement of capacitive sensors for measurement of ring oil film thickness (Ref. 23, Copyright SAGE Publications Ltd. Used with permission)

The capacitance was calibrated against separation between plates using a surface profilometer. The film thickness detected was in the range of 0.4 to 2.5 μm, in the conditions of their tests and they concluded that the lubrication mechanisms in piston/ring systems was essentially hydrodynamic. Capacitance was also the method used by Sherrington and co-workers [25-27].

Their design of the capacitive transducer was based on a charge amplifier capable of generating an output signal proportional to the gap between the transducer and the cylinder. Ducu et al. [28] analysed the criteria for design and calibration of capacitive sensors used in piston/ring systems. They also developed a design procedure for determining the optimum dimensions of the probe for an allowable level of error. They recommended electric circuits employing amplitude modulation instead of frequency modulation, an AC current source-type circuit and a fixed-geometry capacitor for evaluation of the dielectric constant of the oil.

Another electrical method for measuring lubricant film thickness in elastohydrodynamic contacts is the magnetic reluctance method, originally developed by Cameron and Gregory [29]. They successfully applied this method to the measurement of oil film thickness down to less than one micrometer in rolling line contacts formed between parallel-axes rollers. The principle is to determine changes in the magnetic reluctance from measurement of the magnetic flux through the gap between rollers, from which film thickness is obtained. The advantage of the method is that it is insensitive to changes in operating conditions including temperature, speed and lubricant, and therefore insensitive to wear debris and contaminants introduced into the contact. The drawback is that it requires a suitable magnetic circuit to be formed, which inevitably restricts the configuration of the application. The magnetic reluctance method was also used by Poon [30] to measure grease films thickness in elastohydrodynamic contacts, and further developed by Attia and Whomes [31] for rolling sliding contact of rollers.

3. Detection of asperity contact in mixed regime

Due to its simplicity the electrical resistance method was also used relatively extensively for the study of the mixed lubrication regime. The first notable work in this direction was due to Furey [32]. He used a test rig in which the instantaneous and average resistance of a contact formed between a fixed ball and a rotating cylinder were measured. The resistance of the contact was found to oscillate rapidly between very low and very high values, suggesting metallic contacts and full film conditions, typical of the mixed lubrication regime. Friction was also recorded simultaneously. These experiments allowed Furey to investigate the lubrication regime in a wide range of film thickness, i.e. from 0 to 100 percent metallic contact, which correspond to hydrodynamic and boundary regimes, respectively. He stated a value of 10^4 ohms as a criterion of fluid film lubrication, which was considered by Chu and Cameron [33] as arbitrary.

Tallian et al. [34] modified and refined Furrey's technique to accommodate the measurement of electric conductivity of the elastohydrodynamic contacts in a four-ball tester, as shown in Fig. 6. They compared measured and computed values of the duration and frequency of electrical contacts between specimens and extracted estimates of average film thickness as a function of speed and load.

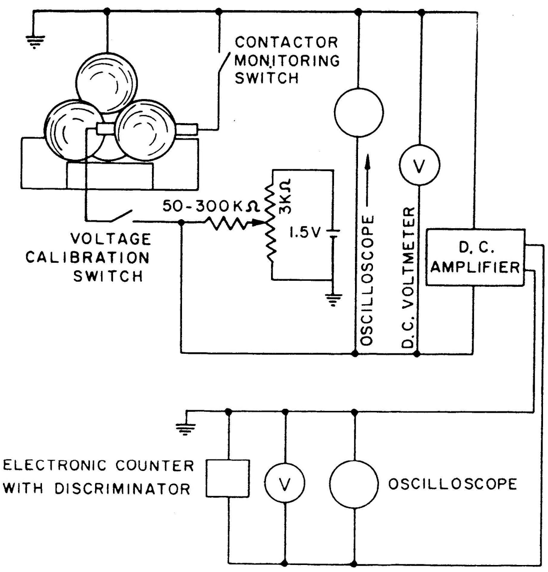

Fig. 6 Schematic of Tallian's conductivity test circuit (Ref. 34, Copyright Society of Tribologists and Lubrication Engineers. Used with permission)

Palacios [35] also evaluated the occurrence of metallic contacts in a four-ball tester using the electrical resistance technique. He correlated the out-of-contact roughness with the number of contacts per unit time and monitored their evolution during the running-in process. Ten Napel and Bosma [36] studied the effect of the surface roughness upon the measurement of elastohydrodynamic film thickness by a capacitive method. They tested a linear contact and observed that there was a marked deviation of the measured film thickness and theoretical values predicted by Dowson and Higginson formula. The error was attributed to the calibration of the film thickness against the capacitance estimated for a capacitor with perfectly smooth surfaces.

Heemskerk and co-workers [37] investigated the film formation in rolling bearings by the capacitive method, using a novel instrument capable of recording metallic asperities interactions. They use this method to investigate the EHD film formation for values of the lambda parameter between 2 and 3. Recently, Chua and Stachowiak [38] have employed electrical capacitance to evaluate the boundary lubrication phenomena of vegetable oils. They allowed for the contributions of the boundary film (over the real area of contact) the fluid film contained in the valleys between asperities and the out of contact capacitance. The real area of contact and the variation of the dielectric constant with pressure were evaluated theoretically.

Guanteng et al. [39] correlated the electrical resistance with the lubricant film thickness and the friction force generated in a mixed lubrication regime EHD contact. They used optical interferometry to map the film thickness across the contact and directly interpreted the electrical contact resistance in terms of film thickness distribution. Lord and Larson explored the film formation of base and fully formulated gear oils in mixed lubrication regime, by measuring the impedance of the contact [40]. This was automatically output as simultaneous values of the resistance and the capacitance of the contact, the former describing the amount of metallic contact and the later showing the separation between the surfaces.

4. Effects of electric field upon lubrication

The application of electrical methods for the study of film thickness in lubricated systems has led to the studies on the effect of the electric field upon the behavior of lubricating films subjected to an electrical field and those aimed at the evaluation of the dielectric properties of lubricants. All these three approaches are related to each other, as it seems that the electric field can change the frictional behavior of lubricated contacts, which in turn modify the heat generated through friction, the viscosity of the lubricant and consequently the film thickness.

Studies on the effect of the electric field upon the life of rolling elements bearings have a long pedigree [41-44]. These studies have focused on the occurrence of pitting stimulated by the passage of the electric current through the bearings of electrical machines. Kure and Palmetshofer [43] stated that the risk of damage occur when the voltage exceeds 0.5 V or the current flow was more than 0.1 A/mm^2, while Prashad [44] found that voltages as low as 200 mV could cause failure of the rolling elements.

Yamamoto and co-workers [45] studied the effect of the applied voltage upon friction and wear characteristics in the mixed lubrication regime. They used a ball-on-pin arrangement and focus on the friction characteristics of elastohydrodynamic contacts in various regimes of lubrication, in the presence of an electric field. A schematic of the electric circuit used to detect the film thickness is shown in Fig. 7. They found that the presence of the electric field caused an oxide film to form at the anode side which changed the friction and wear pattern on the specimens. The element connected to the cathode showed abrasive wear, fact which can be used to obtain favorable running-in.

They also concluded that the presence of the electric field promoted the breakdown of the EHD film in full film conditions. In mixed and boundary regimes frictional characteristics can be improved by the presence of an electric field.

Luo et al. [46] investigated the formation of ordered layers in elastohydrodynamic contacts subjected to an external electric field. They found that film thickness and friction coefficient were related to the voltage applied. A stronger electric field would produce thicker films in pure rolling conditions, while increasing the friction coefficient under pure sliding. Xie and co-workers [47] have studied the lubrication phenomena in the bearings of electrical motors, which are inherently subjected to an electric field. They have reported the formation of gas bubbles in EHD film. In an additional paper Xie et al. [48] have found that the electric current does not affect the thickness of the elastohydrodynamic film formed by paraffin, however it influences the emergence of micro-bubbles around the contact area. They also revealed that addition of ZDDP additive the intensity of the micro-bubbles emergence increases.

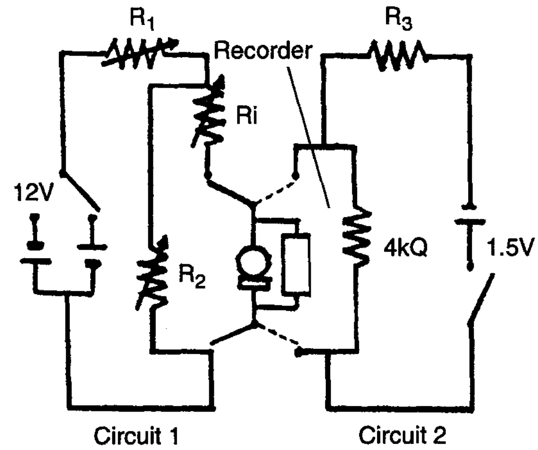

Fig. 7 Electrical circuit for measuring the degree of separation between specimens (Ref. 45, Copyright John Wiley and Sons. Used with permission)

5. Concluding remarks

Electrical methods have been extensively used in the past for the study of film formation in lubricated contacts. These methods, based on the measurement of the electrical resistance and/or capacity are relatively simple to apply and have the advantage that are applied to systems where both specimens are metallic or even to real machine components. There are some limitations to these methods. They are difficult to calibrate mainly because the passage of the electrical current through the lubricant film is greatly influenced by the presence of metallic impurities and by the geometry of the contacting surfaces. The flow of electric current through an elastohydrodynamic contact can cause damage by pitting of the surfaces.

These methods have proved invaluable in understanding the mechanisms of film formation in elastohydrodynamic contacts. They have also provided tools for the study of metallic asperity contact, friction and wear in mixed lubrication regime.

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