Literature review and discussion on measurements of leakage, lubricant film thickness and friction of reciprocating elastomeric seals

Literature Review and Discussion on Measurements of Leakage, Lubricant Film Thickness and Friction of Reciprocating Elastomeric Seals©

M. VISSCHER and A.F.C. KANTERS
Eindhoven University of Technology
Department of Mechanical Engineering
Institute for Power Transmissions and Tribology
W.Hoog 3.110
NL 5600 MB Eindhoven

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Measurements of leakage, lubricant film thickness and friction of seals have been performed in various ways during the last 45 years. However, the question of what really are good methods is still unanswered. Therefore, most methods are analyzed in this paper. The most important conclusion is, that the measurements can be easily disturbed when they are not performed very carefully. Proper interpretation of the results is often difficult, because of lack of information about important details and assumptions.

INTRODUCTION

Experiments on the lubrication of seals have been performed from the beginning of seal research, about 45 years ago (*1*). Various methods have since been used to measure leakage and lubricant film thickness. To measure the friction force, several test rigs have been constructed and many different ways to measure the friction of a single seal have been tried. However, investigation on the suitability and accuracy of all these methods has rarely been reported. Hence, the question of what really are good methods and what accuracy can be obtained is still unanswered.

In this paper, methods used in the past for measurements of leakage, lubricant film thickness and friction are described and discussed, based on the authors' tests and experiences. Though this paper is primarily dedicated to reciprocating seals, use of the experimental methods is not restricted to them.

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LEAKAGE MEASUREMENTS

Leakage measurements are firstly important in practice to judge the performance of a seal. For this purpose, only the net-leakage, which is the difference between leakage at outstroke (out-leakage) and "leakage" at instroke (in-leakage), has to be measured. However, simultaneous measurement of friction and out- or in-leakage also gives information on the actual state of lubrication (*2*). Continuous measurement of out-leakage can help in the study of film thickness variations under transient conditions. Direct measurement of the lubricant film thickness is more appropriate and detailed, of course, but more difficult.

Removing Oil From the Rod

Sampling Oil Dropping From the Rod

Leakage can be measured by removing the leaked oil from the rod (or cylinder wall) and weighing it. A method used very frequently is sampling the oil dropping from the rod as was performed by e.g. Mueller (*3*), Hirano and Kaneta (*4*), Field and Nau (*5*), Fitch (*6*), Schrader (*7*) and Messner (*8*). In this way, net-leakage can be measured and, averaging the leakage over many strokes, the method can

NOMENCLATURE

A	= effective electrical conductive area	$[m^2]$
b	= contact width	$[m]$
C	= electrical capacitance	$[F]$
C_1	= electrical capacitance over the lubricant film	$[F]$
D	= rod diameter or seal diameter at lip	$[m]$
d	= effective electrical conductive width	$[m]$
f	= frequency	$[Hz]$
h	= lubricant film thickness	$[m]$
l	= seal height	$[m]$
R	= electrical resistance	$[\Omega]$
R_1	= electrical resistance of the lubricant film	$[\Omega]$
R_s	= electrical resistance of the seal	$[\Omega]$
V_a	= applied voltage	$[V]$
V_m	= measured voltage	$[V]$
Z_1	= electrical impedance of the lubricant film	$[\Omega]$
ε_0	= absolute electrical permitivity of vacuum	$[F/m]$
ε_r	= relative electrical permitivity	$[F/m]$
ρ	= specific resistance	$[\Omega m]$
ρ_1	= specific resistance of the lubricant oil	$[\Omega m]$
ρ_s	= specific resistance of the seal	$[\Omega m]$

be very accurate. Seperate measurement of in- and out-leakage is, however, not possible.

Oil Absorption

A method to determine out-leakage was used in the very begining of seal research by White and Denny (*9*). They tried to remove the leaked oil by absorption with e.g. blotting paper. This method was also used by Lang (*10*). White and Denny claimed without prove, that all but one molecular layer of oil could be removed in this way. The authors' tests, performed on a sheet of steel, indicate, that an oil film of about 0.25 [μm] thickness can not be removed in this way.

Oil Extraction by a Solvent

A new method was developed to obtain high accuracy without the need for averaging over many strokes. The oil is extracted from the rod by a solvent and the solution is vacuum evaporated, followed by weighing of the residual oil. The average thickness of the oil film on the rod can then be calculated with an accuracy of ± 0.01 [μm] (*2*). Measurement of out- as well as net-leakage is possible.

Measurement of Oil Flow

It is also possible to measure the oil flow necessary to maintain constant pressure in the seal housing. This was done by Field and Nau (*5*), Lindgren (*12*) and Karaszkiewicz (*13*). Field and Nau and Lindgren measured only the average net-leakage of two seals. They, however, reported nothing about the influence of leakage at other components of the system, such as the oil supply pump. Karaszkiewicz tested this influence statically and concluded it to be small. He also analysed the influences of among others pressure variation and temperature. The overall accuracy was estimated to be about ± 3 [mm^3] in leakage volume. The influence of leakage caused by the piston motion of the pump has, however, not been tested.

Karaszkiewicz also measured out-leakage with the same method. To prevent in-leakage, he wiped the leaked oil from the rod before starting an instroke, just as Lang did (see last section). He did not determine the mass of the removed oil for comparison with the oil flow measurement. He tested whether more oil would be removed using by adding a solvent, but did not find much difference. How much oil actually remains on the rod has not been measured.

Optical Methods

A fluorescence method was used by Smart and Ford (*14*), Ford and Foord (*15*) and Koehnlechner (*16*). The essence of this method is, that electro-magnetic radiation of a certain frequency is transformed by oil particles to radiation of a lower frequency. Continuous measurement of out leakage is possible. Smart and Ford used the UV part of the spectrum of a high pressure mercury lamp. Ford and Foord replaced the mercury lamp by a UV laser, because of difficulties with the UV focussing optics, required by the use of a mercury lamp. Tests performed by them, showed fluorescence degradation caused by the UV radiation, so they finally used a blue laser. Koehnlechner also used a blue laser. He further tested the influence of a number of disturbances and concluded the maximum inaccuracy in leakage measurement to be 15 percent.

Electrical Methods

Kambayashi and Ishiwata (*17*) used a method with an electrode mounted above the rod to measure the electrical capacitance over the oil film layer and the air layer in the gap between electrode and rod. Continuous measurement of out-leakage is possible. Use of a single electrode may, however, cause very serious errors due to relative radial motion between the electrode and the rod. Using a second electrode opposite to the first can eliminate this problem (*11*), (*18*). They presented only the measured capacitance without calculating oil film thicknesses from them. The capacitance values given were very small (less than 1 [pF]), making their accuracy doubtful.

LUBRICANT FILM THICKNESS MEASUREMENT

Measurements of the lubricant film thickness, when reproducable and accurate, provide a very valuable insight into the lubrication. They are necessary to test the validity of lubrication theories, and can also be helpful in the development of realistic theories.

Mechanical Method

A mechanical method was used by Schrader for measurements on piston seals (*7*). A pin with a top radius of 0.15 [*mm*] was pressed against the seal surface by a non-iron spring with a force of 0.015 [*N*]. The displacement of the pin was measured with an inductive transducer. A compensation was made to eliminate the influence of fluid pressure.

This method has the disadvantage of disturbance just at the measuring spot. The most serious disturbance is probably the seal deflection: Assuming Hertzian contact and incompressibility of the seal, it can be derived, that the deflection is about 1.5 [*μm*] for an E-modulus of 1000 [MPa] and about 5 [μm] for an E-modulus of 100 [MPa]. So the deflection can be large compared with measured film thicknesses.

Magnetic Induction Method

The first attempts Schrader made, were based on an inductive method (*7*). He used an induction transducer, mounted in the cylinder wall, and a ferrite filled seal. The method proved to be very sensitive, but it was disturbed by pressure dependence of the magnetic permeability of the seal. Besides, the measurements were obstructed by a high wear rate.

Optical Methods

Interferometry

An optical interference method was adapted by Blok and Koens (*19*), Roberts and Tabor (*20*), Field and Nau (*21*), Krauter (*22*) and others. One of the difficulties using interferometry on rubber specimens is the requirement of a smooth reflecting surface. Blok and Koens obtained this by bonding a thin flexible aluminized foil on the surface. Roberts succeeded to produce an optically smooth rubber surface. Field and Nau also used an optically smooth rubber and Krauter used a seal with a thin lacquer coating. Roberts and Tabor as well as Field and Nau used monochromatic light. This has, however, the disadvantage that only a difference in film thickness between two neighboring fringes is known and not the absolute value. To overcome this problem, Field and Nau also used white light, which appeared, however, to be only applicable for film thicknesses less than about 1 [µm]. A probably better solution is using bichromatic light, as was done by Krauter.

Fluorescence

A fluorescence method was used by Kassfeldt (*23*) using a blue laser. Details, e.g. about the accuracy, were not given. Only the dimension of the illuminated point was given to be less than 1 [*mm*], the contact width of the seal being about 5[*mm*]. Proper interpretation of the results is therefore impossible.

Electrical Methods

Capacitive

One of the first direct measurements of the lubricant film thickness was probably performed by Jagger (*24*). He tried mechanical, optical and electrical methods, of which only an electrical capacitive method seemed to be successful. He used a conductive rubber and the capacitance was measured over the whole width of the seal lip (about 1 [*mm*]) and the whole circumference of the shaft. To eliminate the influence of e.g. the resistance of the oil film and the seal, Jagger decided to use direct calibration of the measuring equipment instead of calculating the film thickness from the measured capacitance. Calibration was performed for film thicknesses up to 30 [*µm*] in steps of 5 [*µm*]. Most of the measured film thicknesses were, however, smaller than 5 [µm] and the applicable calibration curve indicates inaccuracies of about 1 [µm]. Nothing has, however, been reported on this matter.

The capacitive method was also chosen by Dowson and Swales (*25*) and Field and Nau (*5*). Field and Nau used carbon black filled rubbers with a specific resistance of about 3 [Ω*m*]. They gave some information on the errors due to inaccuracy of the capacitance measurement, varying from 0 percent at very thin films to about 12 percent at a film thickness of 7.5 [*µm*]. In an earlier paper (*26*), they gave much higher values (up to 40 percent at a film thickness of 5 [*µm*]), though the same instrumentation seemed to be used. How these data were obtained has not been reported, so the origin of this difference is not clear. Field and Nau also stated, that measurements of film thicknesses of less than 0.25 [*µm*] at higher pressures (up to 6.9 [MPa] (*5*)) were inaccurate because of the seal resistance being pressure dependent. This was concluded from calculations, details of which were not given. It puts forward, however, an important point: The influence of the seal resistance seems to be a factor, though the specific resistance of the seals used by Field and Nau was very small compared to that of the oil (about 10^7 [Ω*m*]).

Resistive

Lawrie and O'Donoghue (*27*) measured the electrical resistance between the rod and a conductive seal. The results were only qualitative, indicating contact, partial contact or no contact. Quantitative measurements appeared to be difficult due to pressure dependence of the seal resistance. Wernecke (*28*) used the method quantitatively using carbon black filled rubbers.

Analysis of the Electrical Methods

As we have seen, the seal resistance and its pressure dependence seems to be important. To our knowledge, however, its influence has never been investigated. It is initially important to know what resistance can be expected with a small electrode at one side of the seal (which is commonly the electrode to measure the oil film thickness) and a large one at the other side (e.g. the seal housing). Some preliminary measurements, using the set up of Fig. 1, showed, that the resistance may be estimated by the common formula:

$$R = \frac{\rho l}{A}, \quad [1]$$

in which l is the seal height and A is the effective conductive area. For a circular small electrode, the effective conductive area is:

$$A = \frac{\pi}{4} d^2, \quad [2]$$

in which d is the effective conductive width. It appeared, that d ≈ 2.5 [*mm*] when l = 5 [mm] and the diameter of the smaller electrode is 1 [*mm*] (*11*). Using this estimation, it is possible to give a global analysis of the capacitive and resistive methods.

As an example of the capacitive method, the electrical instrumentation used by Jagger (*24*) is given in Fig. 2. The effective conductive area is now given by:

$$A = \pi D d \quad [3]$$

while the electrode extends over the whole seal circumference. The frequecncy of V_a was 93 [*kHz*] and the diameter

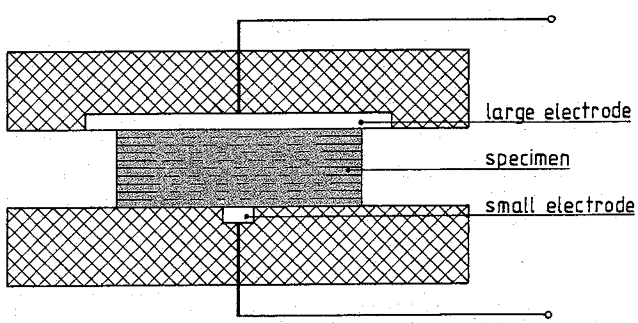


Fig. 1—Test rig for measurement of the effective seal resistance

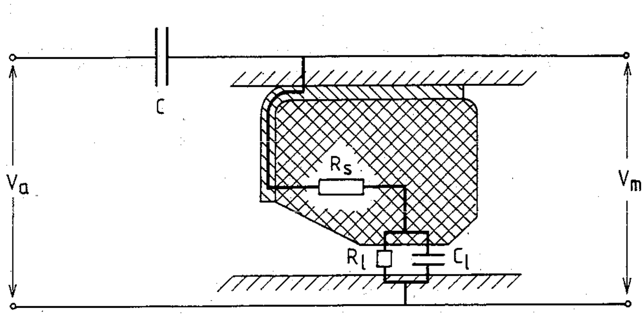


Fig. 2—Electrical instrumentation used by Jagger

D of the seal at the lip was 140 [mm]. It can be derived from his calibration curve, that the capacitance C must have been in the order of 10^{-11} [F] (*11*). This results in a large sensitivity of the set up, but the influence of the seal resistance can be large as well (Fig. 3). Disturbances caused by pressure dependence of the seal resistance were not eliminated by calibration, because the calibration was performed for an undeformed seal. It may be clear, that the design of the test configuration, including the seal, must be performed with great care, when using a capacitive method.

As an example of the resistive method, the electrical instrumentation used by Wernecke is given in Fig. 4 (*28*). Neglecting the seal resistance, the measured voltage is given by:

$$V_m = V_a \frac{Z_1}{Z_1 + R} \qquad [4]$$

in which:

$$Z_1 = \frac{1}{1/R_1 + 2\pi j f C_1} \qquad [5]$$

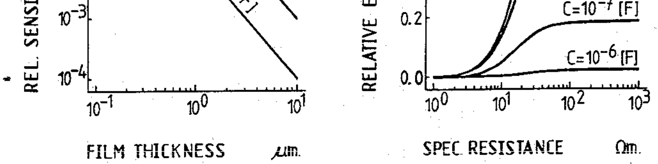
$$R_1 = \frac{\rho_1 h}{A} \qquad [6]$$

and:

$$C_1 = \frac{\varepsilon_0 \varepsilon_r A}{h} \qquad [7]$$

f is the frequency at which the local film thickness at the electrode varies during motion, for V_a is a direct voltage. Wernecke neglected, however, the capacitance, thus introducing an error, which can be up to 30 percent when $f = 10^3$ [Hz] (Fig. 5, (*11*)). Wernecke stated, that frequencies up to 3000 [Hz] may not be filtered to get all important information from the measurements.

To eliminate the influence of the fluctuations in the film thickness, V_a must be a high frequency voltage, e.g 10^5 [Hz], so that the capacitance influence can be calculated. In that case, however, $2\pi f C_1$ is about $10^{-5} A/h$, while $1/R_1$ is about $10^{-7} A/h$, so a capacitance measurement will then be more sensitive.



(a) (b)

Fig. 3—Capacitive method used by Jagger:

(a) Relative sensitivity $\frac{1}{V_m}\frac{\partial V_m}{\partial h}$: ε = 2.3 and b = 1 [mm];

(b) Relative measurement error due to seal resistance: ε_r = 2.3, h = 0.5 [μm], b = 1 [mm], l = 5 [mm] and d = 2.5 [mm]

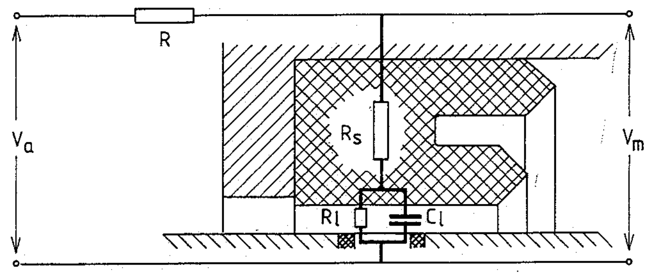


Fig. 4—Electrical instrumentation used by Wernecke

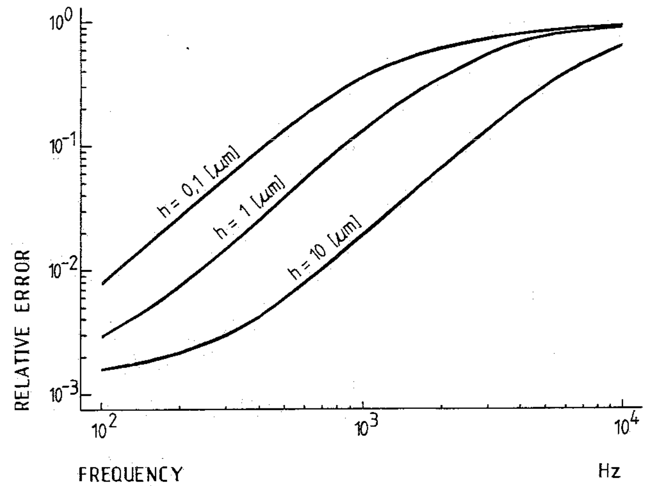


Fig. 5—Relative error of the resistive method used by Wernecke: ρ_1 = 1.1 · 10^7 [Ωm] and ε_r = 2.3.

FRICTION MEASUREMENT

Though measurement of forces is not difficult in itself, measurement of the friction of reciprocating seals appears to have some problems involved. The main problems are the radial rod (or housing) suspension and the seperate measurement of friction at outstroke and instroke. A short literature review will be given, followed by a presentation and discussion of our own test rig.

Friction Measurement on Two Seals

A test rig for friction measurement on two seals (one at outstroke and one at instroke) is given in Fig. 6. This rig was used by Hirano and Kaneta (*4*), who used roller bearings for the radial rod suspension of both the housing and the rod. Field and Nau (*5*) reciprocated the rod and measured the friction on the housing. They also used roller bearings for suspension of both the rod and the housing. Lindgren (*12*) also reciprocated the rod, but the housing was only suspended by the test seals. Lang (*10*) used a similar test rig with addition of two pistons and piston seals.

Friction Measurement on a Single Seal

Use of a Clearance Bush

A possibility to measure the friction at in- and outstroke seperately is using the test rig of Fig. 6, but with one seal replaced by a clearance bush, as was performed by Field and Nau (*5*). The friction of the clearance bush can be calculated, so the friction of the test seal can be determined.

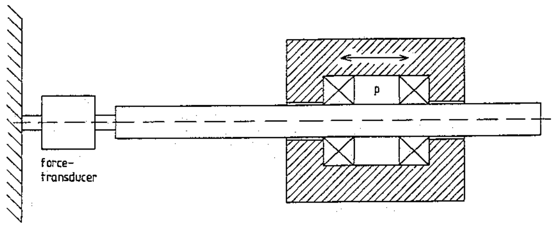


Fig. 6—Test rig for friction measurement on two seals

Field and Nau stated, that the friction of the clearance bush is negligible, however without proving it.

Use of a Rod With One End in the Housing

A test rig, as given in Fig. 7, was used by Kambayashi and Ishiwata (*17*). The rod was radial suspended by roller bearings. Lawrie and O'Donoghue (*27*) also used this principle for piston seals. They reciprocated the rod and measured the friction on the housing, which was suspended by a guide block.

A disadvantage of this rig is, that the pressure is not constant during motion. Mueller (*3*) and Sick (*29*) eliminated this disadvantage by using a second rod, which reciprocated 180° out of phase. Another disadvantage is the additional force on the rod and housing, caused by the fluid pressure. This force will often be much larger than the seal friction, so very accurate measurement of the fluid pressure is required.

Division of the Rod

Gawrys and Kollek (*30*) and Messner (*8*) used a rod, which was divided into two parts (Fig. 8). The two rod parts are connected by a force transducer, so that the friction of a single seal is measured. To avoid influence of the fluid pressure, the space between the rod parts is sealed with a rubber sleeve. Messner used a piezo-electric force transducer. This minimizes the sleeve stress, contributing to the force, as the piezo-electric transducer has a high stiffness. It has, however, a large zero point drift at quasi-static loads, requiring new zero-point calibration before every new measurement. Gawrys and Kollek did not report what transducer they used, but they estimated the influence of the sleeve experimentally to be about 3 percent.

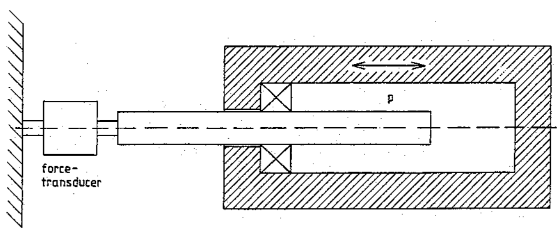


Fig. 7—Test rig with one rod end in the housing to measure the friction of a single seal.

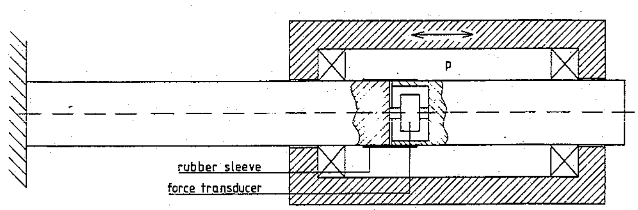


Fig. 8—Test rig with rod divided into two parts to measure the friction of a single seal.

The sleeve can also disturb the measurements by extrusion into the gap between the two rod parts. this is a likely occurrence, for Gawrys and Kollek measured at pressures up to 20 [MPa] and Messner up to 30 [MPa]. Nothing has, however, been reported on this factor.

The Authors' Own Test Rig

The authors' test rig is of the type in Fig. 6 with the possibility of replacing one seal by a clearance bush (*2*). At first, the bush was cylindrical and the rod was suspended by and positioned with roller bearings.

Clearance Bush

As appeared, that the rod was easily pressed against the wall of the bush, due to small misalignments, it was decided to replace the cylindrical bush by a tapered one, resulting in a hydrostatic bearing. The friction of the bush has been calculated and may be in the order of the seal friction. The calculations have been verified experimentally (*31*).

Rod Suspension

The radial rod suspensions introduced some problems when the seals had a large radial stiffness and were not closely identical. This led to high radial loads on the suspensions, resulting in significant friction. These disturbances could be recognized from the measured friction curve. Although their occurrence could be prevented by selecting the seals, as was done for the experiments for the authors' last paper (*2*), it was decided to redesign the rig (Fig. 9). The rod is now suspended by the seals, making the individual radial seal loads clearly defined and small. Radial rod displacement is made possible by two elastic universal joints.

A simple test rig was designed to measure the radial seal stiffness (Fig. 10). The measurement is performed by loading the rod with one or more weights and registering the radial rod displacement after a certain time to eliminate viscous effects. When required, a fluid pressure can be applied. With this test rig, it can be investigated, how and to what extent a radial loading influences the seal deflection. This knowledge may be of importance at interpretation of leakage and friction data obtained with our test rig.

CONCLUSIONS

Many methods have been used in the past to measure leakage, lubricant film thickness and friction. Important aspects are sometimes neglected and assumptions are often made without proving them. Interpretation and comparison of reported experimental results are, therefore, diffi-

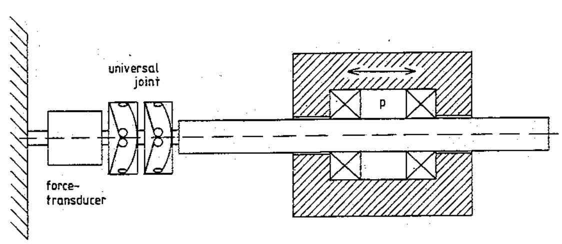


Fig. 9—Final design of our test rig

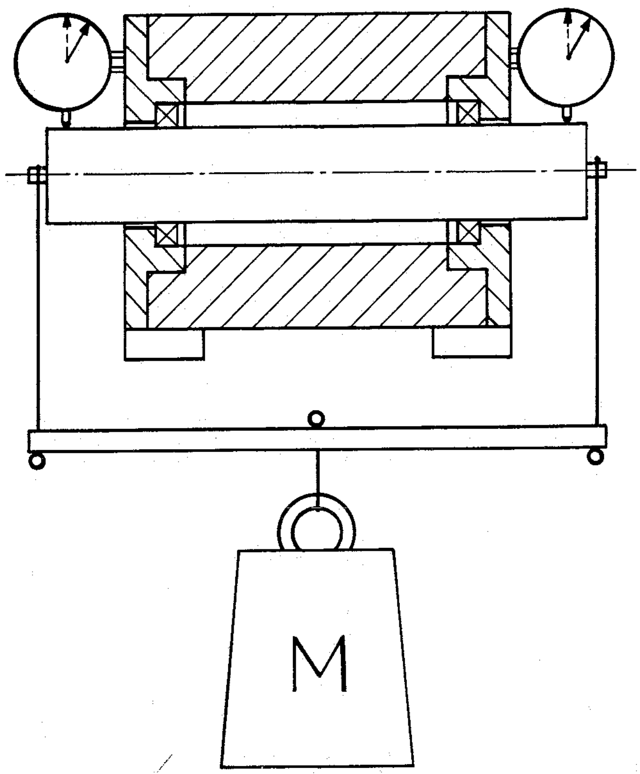


Fig. 10—Test rig for measurement of radial seal stiffness

cult. Some conclusions, based on theoretical and experimental investigation of these methods are listed below:

Leakage Measurements

For measurement of out-leakage, the fluorescence and capacitive methods seem to be the most attractive, as continuous measurements are possible. The accuracy is, however, still low. These methods will, therefore, be further investigated. The method using extraction of oil by a solvent can be very accurate and will be helpful to evaluate other methods.

For net-leakage measurement, sampling the oil dropping from the rod can be accurate, but is very time consuming. Measuring the oil flow can be a good alternative when pump leakage can be kept low. The extraction method is also a good alternative, as it is very accurate for a single or a few strokes.

Lubricant Film Thickness Measurements

The capacitive method can possibly be used, but requires special highly conductive seals. More research on this matter is required. Optical methods seem to be more reliable. Interferometry can be used on smooth surfaces. The fluorescence method is probably suitable for more or less rough surfaces and will be investigated in the near future.

Friction Measurements

These measurements are easily disturbed by additional suspensions. Radial suspension by the seals eliminates these disturbances and imposes a well defined loading on the seals. Replacement of one seal by a tapered clearance bush allows measurement on a single seal. The friction of the clearance bush, however, may not be neglected. Division of the rod into two parts is probably a good alternative, but requires additional investigation.

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Meeting Calendar

December 4-6— The Institution of Engineers Australia is sponsoring an International Tribology Conference 1990 co-sponsored by the Australian Section of STLE. The conference is entitled "Putting Tribology To Work: Reliability and Maintainability through Lubrication and Wear Technology." For more information, contact The Conference Manager, The Institution of Engineers Australia, 11 National Circuit, BARTON ACT 2600, Australia. Telephone: 06-2706-522. FAX: 06-2706-530. Telex: AA 62758.

December 4-6— The main methods of predictive maintenance by oil analysis will be described in the course titled "Predictive Maintenance and Fault Diagnosis by Oil Analysis". Optical emission spectroscopy, other physical and chemical tests, and laboratory computerization will be discussed. Emphasis on practical application; instruments at course to permit hands-on experience, and students encouraged to bring used lubricant samples to The Center for Maintenance Technology, Fairleigh Dickinson University, 285 Madison Ave., Madison, NJ 07940. Phone: 201-593-8666. Contact the university direct for registration or further information. Fee $545.

December 6— The fifth BP-IMechE Tribology Lecture will be held by Dr. B. S. Nau. Dr. Nau of the Fluid Engineering Centre, BHRA will present his paper "On Some Fundamental Factors Affecting Rotary Mechanical Seal Performance." Admission is free and tea will be served at 5:30 p.m. The Tribology Group Committee is arranging an afternoon seminar on "Reciprocating Seals and Seal Construction Materials" as a curtain-raiser to Dr. Nau's presentation. For further information please contact Maria Clarke at IMechE HQ, 01-222-7899 Ext. 213.

December 18-20— Engineering Physics Division Conference University of Warwick session contributed by Tribology Group. "Tribology in Extreme Environments" on Wednesday, 10:30 a.m. to 1:00 p.m. Other topics include "Tribology in Space," "Friction of Rubber on Ice," "Lubricants at High Temperatures" and "Tribology in the Mining Environment." For further information, please contact, The Meetings Officer, The Institute of Physics, 47 Belgrave Square, London SW1X 8QX. Telephone: 01-235-6111. Fax: 01-2596002.

January 7-11— UCLA Extension presents a mechanical engineering short course this winter, "Miniature Refrigerators for Cyrogenic Sensors and Cold Electronics." This course provides a thorough introduction to regenerative and recuperative cyrocoolers, miniature refrigerators used to achieve and maintain cryogenic temperatures of less than 120K. The course meets from 8 a.m. to 5 p.m. at the UCLA Extension Building, for a fee of $1295. For complete details, call UCLA Extension, (213) 825-1047, or write: UCLA Extension, Engineering, 10995 LeConte Ave., Ste. 530, Los Angeles, CA 90024.

January 8-10— The "Rolling Bearing Institute," will offer bearing training courses at Villanova University. The course is designed for maintenance, service, machine repair, and plant/facility engineering staff of an industrial plant, OEM facility, institution, public safety or commercial building which uses rolling bearings and related equipment. The three day program, "Rolling Bearing Life Improvement," at Villanova is 15 miles from Philadelphia. The three day fee is $650 per participant. For brochures about this program, please call the Villanova University office of Continuing Education at (215) 645-4310.

January 14-18— Introduction to Hydraulics Seminar will be held at the Milwaukee School of Engineering. This seminar is co-sponsored by the National Fluid Power Association (NFPA) and held with the cooperation of the Fluid Power Institute and the Applied Technology Center at Milwaukee School of Engineering. This week long seminar is designed to acquaint individuals with the field of fluid power and to provide a practical working knowledge of this important and growing industry. The fluid power industry has gained increasing importance over the years with applications in heavy equipment, the automotive and marine industries, machine tools, agriculture, aircraft, robotics, space vehicles, and even medicine. The seminar fee is $795 which includes book, all handout material, break refreshments and a graduation luncheon. For more information, contact Susan Hoerchner, Continuing Education, Milwaukee School of Engineering, P.O. Box 644, Milwaukee, WI 53201-0644.