Oil Film Formation of Reciprocating Seals Observed by Interferometry

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Oil film thickness in rubber piston seals is measured by interferometry. Optimized optics and fluids enable clear interferograms. The oil film thickness on the contact area is measured during reciprocating motion. When the oil film formed on the contact area is sufficiently thick, monochromatic interferometry is applied to measure the variations in oil film profile. Under sealing condition, where the oil film is thin and even, the mean oil film thickness is measured by means of white light interferometry. The measurement results of oil film thickness correlate with the friction force.

Keywords: piston seal, reciprocating seal, interferometry, oil film thickness, friction

1. Introduction

In order to improve the design and operation of reciprocating seals, it is essential to understand how oil films form on seal surfaces. A number of theoretical studies describing oil film formation have been reported. In the 1960s, the inverse theory of hydrodynamic lubrication was proposed [1,2], which provided a way to predict oil film formation from the contact pressure gradient of a seal. This theory has been developed with computational techniques [3,4]. Attempts were also made to physically measure oil film thickness. One of the first direct measurements was reported by Jagger [5], which was performed by an electrical method. Since then, several measurement methods have been reported, such as a magnetic resistance method [6] and a fluorescence method [7]. Interferometry is another possible method for measuring oil film thickness. The advantage of interferometry is that the variations in oil film thickness distribution can be monitored on a short time scale, which is difficult to achieve with other methods. Blok and Koens first reported the application of interferometry to the measurement of oil film variations on a rod seal during the reciprocating cycle [8]. Other researchers have measured similar variations on model seals [9,10] and rod seals [11].

The present research is focused on measuring the variations in oil film thickness on piston seals. A new apparatus based on interferometry is developed, which provides clear interferograms of the reciprocating motion.

2. Optimization of optical system

The difficulty of applying interferometry to rubber seals mainly lies in the low reflectivity of the rubber surface. Most of the incident light is absorbed by the rubber surface, thus interferograms tend to be unclear. Some researchers overcame this problem by improving the reflectivity of the rubber surface. Blok and Koens used a thin plastic aluminized foil bonded on the surface [8]. Krauter applied a thin lacquer coating to a seal surface [11]. However, these treatments might cause changes or irregularities in the surface properties. Another method intended to improve the reflectivity of the surface is to use an appropriate combination of rubber and fluid [9,12]. The reflectivity of the surface depends on the magnitude relation of the refractive indices of the two media at the interface. The reflection coefficient \( R_{ij} \) at the interface of media \( i \) and \( j \) is given by

\[
R_{ij} = \left( \frac{n_i - n_j}{n_i + n_j} \right)^2
\]

where \( n_i \) and \( n_j \) are the refractive indices of the respective media. Hence, the refractive indices of the two media at the interface should be sufficiently different from each other to obtain clear interferograms. In the present study, fluorocarbon oil (BARRIERTA, NOK Klueber) showed good results in combination with a seal specimen that was made of NBR without any surface treatments.
3. Monochromatic interferometry

3.1. Test apparatus

The apparatus was designed for the purpose of measuring the oil film thickness between rubber piston seals and a cylinder. A schematic of the apparatus is shown in Fig. 1. It consists of a glass cylinder, a linear actuator and a microscope. A seal specimen is mounted on a fixed piston. A transparent glass cylinder is connected to the linear actuator and slides over the seal lip. The friction force and the cylinder position are measured simultaneously by a load cell and a displacement sensor, respectively. The contact area is observed under microscope. The light source is a mercury lamp combined with a band pass filter, which produces a monochromatic light of wavelengths of 436 or 546 nm. Interferograms are recorded by a high speed camera at 500 fps. The oil film thickness distribution is calculated by counting the fringe orders of interferograms. The oil film thicknesses \( h \) at bright fringes are expressed as follows

\[
h = \frac{2N + 1}{4n} \lambda, \quad N = 1, 2, 3\ldots
\]

where \( N \) is a fringe order, \( \lambda \) is the wavelength of incident light and \( n \) is the refractive index of oil. Note that there is in general a phase change in the light when it is reflected off the surface. In this study, the phase change is assumed to be \( \pi \) for simplicity sake. The absolute value of the fringe order is determined by comparing the oil film profiles obtained under the incident light at wavelengths of 436 and 546 nm.

3.2. Test conditions

Tests were conducted under the conditions listed in Table 1. The reciprocating motion is sinusoidal wave with a frequency of 0.5 Hz and a stroke of 4.0 mm. Here, “fully flooded condition” means that oil is filled both sides of the seal, and “sealing condition” means that oil is filled only on the lip side. Figure 2 shows the cross section of a seal specimen. The outer lip surface was molded to a surface roughness of 0.07 \( \mu \)m Ra.

3.3. Test results

Figure 3 shows interferograms and film profiles of the reciprocating motion under fully flooded condition. The interferograms shown here were taken with the incident light of 546 nm. Here, “instroke” means that the cylinder moves from the heel side toward the lip side and “outstroke” means the movement from the lip side toward the heel side. At the bottom dead center of the stroke (i), the interferogram at the contact area showed no fringes, which means the oil film thickness was thinner than that of the first fringe order (105 nm). The fringe was observed during the instroke, which moved with the cylinder movement ((ii) ~ (iii)). The speed at which the film front moved across the contact area was half the speed of the cylinder. Similar results were

![Fig. 1 Schematic of test apparatus for monochromatic interferometry](image)

![Fig. 2 Shape of seal specimen](image)

Table 1 Test conditions for monochromatic interferometry

<table>
<thead>
<tr>
<th>Seal material</th>
<th>NBR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness of material</td>
<td>93 (IRHD)</td>
</tr>
<tr>
<td>Frequency</td>
<td>0.5 Hz</td>
</tr>
<tr>
<td>Stroke</td>
<td>4.0 mm</td>
</tr>
<tr>
<td>Bore diameter</td>
<td>40 mm</td>
</tr>
<tr>
<td>Temperature</td>
<td>25°C</td>
</tr>
<tr>
<td>Pressure</td>
<td>Ambient</td>
</tr>
<tr>
<td>Oil and viscosity</td>
<td>BARRIERTA J 100</td>
</tr>
<tr>
<td></td>
<td>(95 mm²/s @ 40°C, 13 mm²/s @ 100°C)</td>
</tr>
<tr>
<td>Lubrication condition</td>
<td>Fully flooded, Sealing</td>
</tr>
</tbody>
</table>

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reported in earlier studies [9,10]. On the outstroke, the trailing edge of the oil film moved toward the heel side at half the speed of the cylinder, and near the center of the stroke (vi), the fringes disappeared. Overall, the oil film during the instroke was thicker than that during the outstroke. Therefore, oil is pumped from the heel side to the lip side under this condition. The relation between the cylinder position and the friction force is shown in Fig. 4. Symbols (i) ~ (vi) correspond to those in Fig. 3. In the early stage of the instroke ((i) ~ (iii)), the friction force decreased due to the formation of the thick oil film across the contact area. After the thick oil film covered the contact area, the friction force reached a minimum ((iii) ~ (iv)). During the outstroke, the friction force increased until reaching a maximum at the point (vi) where the thick oil film disappeared.

Under sealing condition, the oil film profiles were different from those under fully flooded condition. As shown in Fig. 5, interferograms showed no fringes across the reciprocating cycle, which means that the oil film thickness was even and/or thinner than 105 nm. However, it was difficult to distinguish between them from the interferograms. For this reason, the oil film thickness could not be obtained under this condition.

Figure 6 shows the friction curve. The friction forces during the instroke and outstroke were symmetric with respect to the x-axis. This result indicates that the oil film thickness during the instroke and outstroke were almost equal.
4. White light interferometry

4.1. Test apparatus

As discussed above, the measurement of the oil film thickness by monochromatic interferometry is limited to the case where the oil film is relatively thick and uneven. Thus, this method is not applicable to the measurement of the oil film thickness under sealing condition. In order to overcome this drawback, white light interferometry was applied instead of monochromatic interferometry. In white light interferometry, the absolute value of the oil film thickness is presented as a color change, which allows for the measurement of even oil film thicknesses.

Figure 7 shows the test apparatus for white light interferometry. This is similar to that for monochromatic interferometry, but different in optical setup. A halogen lamp that provides a nominally white light is used as the light source. In general, there are two methods of calculating the oil film thickness with white light interferometry. One is an image processing method recently presented by Gustafsson et al. [13] and Hartl et al. [14]. This method matches particular colors with film thickness values calibrated with known geometric shapes. The other is spectral analysis of reflected light first reported by Johnston et al. [15]. In this method, the film thickness is calculated from the intensity profile of the spectrum. In the present study, the latter method is used. Interferograms obtained through the glass cylinder are detected by a spectrometer (PMA-11, Hamamatsu Photonics). The spectrometer analyzes spectrum averaged at the center of the contact zone every second.
with an exposure time of 0.02 seconds. The effective light-receiving area of the optical fiber of the spectrometer is 1 mm in diameter, and the magnification of the microscope is 5x. Hence, the measuring area is within about 0.2 mm in diameter. The wavelength resolution of the spectrometer is 3 nm and the detectable wavelength range is between 300 and 800 nm. The oil film thickness is calculated by fitting the theoretical spectrum to the measured spectrum. The total intensity of the reflected light $I_R$ at a wavelength $\lambda$ is expressed as follows:

$$I_R = I_1 + I_2 + 2\sqrt{I_1I_2}\cos(4\pi h/\lambda n + \pi)$$  \hspace{1cm} (3)

where $I_1$ and $I_2$ are the intensities of the reflected light from glass/oil and oil/rubber interfaces respectively and $n$ is the refractive index of oil.

4.2. Test conditions

A cross sectional view of a seal specimen is shown in Fig. 8. The outer lip was molded to be end-rounded with a curvature radius $R$ of 0.6 mm. Test conditions are shown in Table 2. Due to the slow time resolution of spectrometer, measurements were carried out in the steady state condition; at a constant speed and a long stroke length of 20 mm. The sliding speed was varied from 1 to 40 mm/s. The mean oil thickness was measured at the mid-point of the stroke.

4.3. Test results

Figure 9 shows a typical measurement result of the friction force and the cylinder position during reciprocating motion at the speed of 5 mm/s with BARRIERTA J 100. Except for stroke ends, the friction force was constant and the interferograms showed little change, which means that the oil film was in a steady state during the cylinder movement. The interferograms are illustrated in Fig. 10. Overall, the color distribution along the sliding direction of the contact area was almost even, although there were small fluctuations due to the roughness of the seal surface. Therefore, the measured oil film thickness was regarded as a mean value of the oil film thickness distribution across the whole contact area. The intensity profile analyzed by the spectrometer is shown in Fig. 11. The theoretical spectrum was fitted to the measured spectrum. In this case, the mean oil film thickness was calculated to be 250 nm from Eq. (3).

The mean oil film thicknesses during reciprocation motion were measured at various sliding speeds and oil viscosities. In Fig. 12, the mean oil film thicknesses are
plotted against a non-dimensional duty parameter $G$. Here, $G$ is defined as follows:

$$G = \frac{\eta u}{P/L} \quad (4)$$

where $\eta$ is the viscosity of oil, $u$ is the sliding speed, $L$ is the circumferential length of the cylinder bore and $P$ is the contact force. From the inverse theory of hydrodynamic lubrication, the oil film thickness at the point of maximum pressure of a seal is expected to be proportional to $G^{1/2}$ in hydrodynamic lubrication [2].

The measured values of the mean oil film thicknesses were in proportion to $G^{1/2}$ over the measurement conditions, which agreed with the theory. Comparing the outstroke and instroke, little difference was found in the mean oil film thickness. Similar tests results were reported by Nau et al. [16], where a capacitance probe was used to measure the oil film thickness on a rectangular rubber seal. According to the inverse theory of hydrodynamic lubrication, the oil film thickness is determined by the pressure gradient on the contact area. Hence, the oil film thickness during the instroke should be thicker than that during the outstroke. This presumption is based on the premise that a fully hydrodynamic film exists between the seal and cylinder. In fact, however, the amount of oil pumped back cannot be more than that left after the outstroke. Consequently, the oil film thickness during the instroke is equal to that during the outstroke, when no leakage occurs between the seal and cylinder. This result corresponds to the friction property in Fig. 6.

Figure 13 shows the relation between the coefficient of friction and $G$ during reciprocating motion. The coefficient of friction showed a similar tendency to that of the mean oil film thickness: the coefficients of friction during the outstroke and instroke were almost identical in the region of $G > 10^{-3}$. However, in the region of $G < 10^{-3}$, a discrepancy in the coefficient of friction was seen between the outstroke and instroke. This may be due to the fact that micro asperities on the rubber surface break through the thin oil film and cause partial contact with the cylinder surface.

5. Conclusions

The observations of the oil film formation of piston seals were carried out by means of interferometry. Optimization of the optical system made for clear interferograms. Under fully flooded condition, the variations in oil film profiles were obtained using monochromatic interferometry. The friction properties were correlated with the oil film formed on the contact area. Under sealing condition, white light interferometry
was applied for the measurement of the mean oil film thickness on the contact area. The mean oil film thickness was almost equivalent during the outstroke and instroke, which indicates that the leaked oil was recovered during the instroke.

References


