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Optical profilometry and its application to mechanically inaccessible surfaces

Part II: Application to elastomer/glass contacts

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In part I, the principles of focus error detection were given and its application to roughness measurements through a glass plate on the surface were discussed. In this part, examples of such measurements are presented. These examples are related to the lubrication problem of rough elastomeric surfaces, as studied in seal research programs. Measurements are shown for the statically loaded contact between a smooth glass plate and a rough elastomer, both with and without a liquid in the contact area. The profile measurement for the dry contact is unreliable, but the real area of contact can be derived. Considering the dynamic situation of a sliding, lubricated contact, preliminary, qualitative measurements show that film thickness variations are detected. Finally, the focus error detection method is compared with other methods, which can in principle be used for these measurements, and proves to be a good alternative.

Keywords: optical profilometry; surface roughness measurement; contact mechanics; real area of contact measurement; roughness deformation measurement; lubrication; tribology; film thickness measurement

Introduction

In part I of this article,¹ the principles and performance of optical profilometry by means of focus error detection have been discussed, as was its application for measurement through a transparent layer on or near the scanned surface. In this part, some measurements will be presented by way of illustration and to show the possibilities of optical profilometry for such measurements.

The measurements presented below originate from the reciprocating elastomeric seal research project at Eindhoven University. Kanters^{2,3} found that the seal's surface roughness has a significant influence on the leakage and friction. This influence was not as expected due to asperity flattening in the lubricated contact, which already occurred when the surfaces were fully separated by the lubricant film. Future research will therefore focus on the roughness deformation in the contact area. The practical significance of this investigation is development of

high-precision hydraulic and pneumatic cylinders, which requires better insight into the frictional behavior of the seals.

The measurements shown in this part of the article concern the roughness deformation under static load, which is of importance for pneumatic applications where the seals are generally hardly lubricated. Further measurements shown deal with the lubrication problem at sliding motion between the elastomer and a transparent rigid body, which is of importance for hydraulic seals.

Static contact situation

In the measurements under static load, a 1.2-mm thick glass plate is pressed onto a polyurethane surface (*Figure 1*) with an E-modulus of 45 MPa (linearized for small strain).⁴ The deformed roughness texture is measured with the focus error detection system introduced in part I, operating in the closed loop mode. The spherical aberration introduced by the glass plate is compensated for by the specially designed objective lens as discussed in part I.⁴ Therefore, the focus spot is diffraction limited and has a diameter of about 1 μm .

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Figure 1 Scanning through a loaded glass plate on the surface (P is the contact load)

Figure 2 Undeformed roughness texture of the polyurethane test plate. Measured area, $500 \times 200 \mu\text{m}$; sample distance, $2 \mu\text{m}$ (in both directions)

A scan of the undeformed roughness texture of the polyurethane is shown in *Figure 2*. The standard deviation (σ or R_q value) of the roughness height distribution is about $0.66 \mu\text{m}$. Two measurement series are performed: one with a liquid in the contact area, between a glass plate and the polyurethane surface (wet contact), and the other without the liquid (dry contact).

As discussed in part I and by Visscher,⁴ the liquid in the contact area is needed to obtain proper measurements of the (possibly deformed) roughness profile. In the dry contact situation, the roughness measurement is seriously disturbed by reflection on the lower glass surface. However, the real area of contact can be determined accurately, as will be shown below.

The wet contact

The liquid in the contact area was an oil mixture of 75% Shell Ondina 15 and 25% Shell Ondina 68, which have a dynamic viscosity of $0.03 \text{ Pa}\cdot\text{s}$ and $0.21 \text{ Pa}\cdot\text{s}$, respectively, at 20°C .

The accuracy in the height measurement is not necessarily equal to the value of $0.01 \mu\text{m}$ mentioned in part I because this value is true for a surface reflectance of at least 4%. The reflectance on

* The elastomer's index of refraction could not be determined accurately, but is about 1.5, i.e., almost equal to the index of refraction of the glass and the liquid. A higher reflection on the liquid to elastomer interface will be obtained when using a liquid (and glass) with a significantly higher index of refraction, but this is hard to obtain. See Visscher⁴ for details.

Figure 3 Roughness texture at an average contact pressure of 0.03 MPa (measurement with liquid in the contact area). Measured area, $500 \times 200 \mu\text{m}$; sample distance, $2 \mu\text{m}$ (in both directions)

the liquid to elastomer interface is much smaller, as discussed by Visscher⁴, but tests showed that the accuracy is still reasonable (better than 10%), provided that the laser power is high enough.

Figure 3 shows the deformed roughness texture in the loaded contact. Some flattened areas (indicated by A, B, and C) are found but the R_q value is hardly reduced ($R_q \approx 0.63 \mu\text{m}$). Increase of the load hardly affects the roughness texture: neither the roughness height nor the dimension of the flattened areas are changed at increase of the contact load. This indicates that the load is largely supported by the liquid and not by asperity contact. More details on this subject are given by Visscher,⁴ Visscher, et al.,⁵ and Hendriks.⁶

The dry contact

In the dry contact situation, measurement of the deformed roughness profile is not possible, but the real area of contact can be determined by measuring the photodiode signals, as illustrated in *Figure 4*, where the measured photodiode signal $A (= A_1 + A_2)$ is shown (see part I of this paper for the signals).

Outside the real contacts, the (negative) signals are at a high level (roughly between -1 and -1.5 V) due to a relatively high reflectance of about 4%. Variations in the signals are caused by the surface slopes and perhaps also by interference.⁶ In the real

Figure 4 Photodiode signal A measured in the contact of elastomer and glass

contacts, the reflectance is much lower ($<1\%$) because the elastomer and the glass have an almost equal index of refraction⁷ and the photodiode signals reach their lowest (negative) level of about -0.27 V (see 1–9 in Figure 4). The real area of contact can therefore be determined by counting the number of points where the photodiode signals are at this low level.

Some results of a measurement are given in Figure 5, showing the real contacts at the same load but at two different times after loading. Apparently the real area of contact is increased in time due to creeping of the elastomer, which stops after about 2 hours. Other measurements showed significant increase of the real area of contact at increased load. These measurements are presented and discussed by Hendriks⁶ and by Hendriks and Visscher.⁷

The accuracy in the measured real area of contact is determined by interference, the limited lateral resolution, and small differences in the reflectance between individual contacts. Just outside a real contact the reflectance is still small due to interference. This yields an uncertainty in the position of the contact boundary and therefore overestimation in the measured real area of contact. This uncertainty is larger

when the asperity slopes are smaller. For our surface, with an average asperity slope of 0.1, the uncertainty in the location of the contact boundary due to interference is smaller than $1\text{ }\mu\text{m}$. Therefore, the uncertainty due to the limited lateral resolution, determined by the focus spot diameter of about $1\text{ }\mu\text{m}$, is larger, and the accuracy in the measured size of an individual contact is determined by this lateral resolution. Especially at higher loads, where the individual real contacts are large, the accuracy will be better than 1% .⁶

Considering the accuracy in the total measured real area of contact, it must be noted that there are small differences in reflection (and therefore in the level of the photodiode signals) between individual contacts, as illustrated in Figure 6a. To include all contacts in the measurement, all points at the lowest level $A^{(1)}$ and at the higher levels (e.g., at level $A^{(2)}$) must be counted. According to Hendriks,⁶ this can be easily evaluated using the histogram of the measured photodiode signal because the maximum in the histogram appears to correspond with the lowest level of the signal in the contact spots (Figure 6b). The estimated real area of contact is then determined by $n^{(1)} + n^{(2)}$ in this example.

(a)

(b)

Figure 5 Measured real contact areas. Load $P = 220$ N. (a) Immediately after loading. (b) After 135 min, when the creep has nearly stopped

(a)

(b)

Figure 6 (a) Differences between photodiode signal A in different contacts. (b) Histogram of the measured photodiode signal A . The real area of contact is estimated by $n^{(1)} + n^{(2)}$

Obviously the real area of contact is overestimated in this way, as shown for contact 2 in Figure 6a, and Hendriks found that this overestimation can be as much as 15%. A higher accuracy, better than 1% as stated above, will be obtained when the areas of the individual contacts are evaluated separately, but this has not yet been performed.

Dynamic contact situation

Considering the dynamic situation, preliminary measurements were performed on the lubricated contact of a polyurethane specimen sliding over a smooth and flat rigid body (Figure 7). Until recently only the (nominal) film profile was determined qualitatively to test the ability of the focus error detection system for this purpose, and the results are shown below. The ultimate goal is to measure both the nominal film thickness quantitatively and the (possibly deformed) roughness profile superimposed thereon.

The transducer

A new focus error transducer was designed to cope with the specific requirements for the dynamic film thickness measurements.⁴

Firstly, a dynamic range of 1 MHz is required to realize a sample distance of 1 μm at a maximum sliding velocity of 1 m/s. Consequently, the objective lens must be fixed in the rigid body, and measurements will be performed in the open loop mode (see part I).

Secondly, a window thickness of 2 mm is chosen to withstand a local contact pressure of 5 MPa (see Visscher⁷ for details). A consequence of this window thickness is that the special objective lens from the compact disk transducer cannot be applied (see part I). Instead a normal, diffraction-limited lens is used, and the numerical aperture is reduced to 0.2 to keep the spherical aberration small enough, according to Equation (5) in part I. The focus spot diameter is now about 2 μm , and the measurement range is about -15 to $+15$ μm .

Figure 7 Set up for the dynamic measurements: lubricant film thickness measurement

Simultaneous measurement of the radial error signal, necessary to eliminate the slope influence in the open loop mode (see part I or Visscher⁴), is not yet possible. Therefore, quantitative measurements have not been performed at present, but a new electronic amplifier is being designed to include measurement of the radial error signal

The elastomeric specimen

The specimen used is a cylindrical piece of polyurethane with a radius of 5 mm and an E-modulus of about 45 MPa, linearized for small strain.^{4,7} The contact width $2b$ (Figure 8) can be estimated by Hertzian theory.

Figure 8 Measured focus error signal versus the lateral position x : —, measured curve; ---, expected curve. (a) At a contact load of 2 N. (b) At a contact load of 10 N. (c) At a contact load of 40 N. (b is half the contact width)

The measurements

Two series of measurements were performed. Series 1 was meant to test the ability of the transducer for measurement of the macroscopic shape of the loaded specimen when a lubricant is present in and near the contact area. This test is important because the reflectance on the elastomeric surface will be very low due to the presence of the lubricant, yielding a low focus error signal. Both the sliding velocity and the oil viscosity were low, yielding a lubricant film in the contact area thinner than $0.06\text{ }\mu\text{m}$.⁷

Series 2 was used to test whether differences in the lubricant film thickness are determined. Therefore, a high-viscosity oil was used, and different higher velocities were applied.

The results of series 1 are shown in *Figure 8*, where the solid line is the real measured curve and the dot and dash line is the curve expected from the specimen's geometry. The Hertzian half contact width is indicated by b . The increasing deviation of the measured curve from the expected curve and the final decrease in the measured curve at larger values of $|x|$ is caused by the fact that the focus error curve reaches its maximum at a gap height z of about $25\text{ }\mu\text{m}$.

The measured curve compares qualitatively well to the expected, theoretical curve. The increased contact width due to increased load is clearly detected. The ripples in the measured curve are probably caused by the surface roughness of the elastomeric specimen, but is not important in these preliminary tests.

The results of series 2 are shown in *Figure 9*. Now the Hertzian contact width is equal for all three measurements because the contact load is constant, but the film thickness varies. According to Visscher⁴ the theoretical central film thickness h_c (at position $x = 0$) is as follows

$$\begin{aligned} h_c &= 0.26\text{ }\mu\text{m} \text{ for velocity } u = 1\text{ mm/s} \\ h_c &= 1.14\text{ }\mu\text{m} \text{ for velocity } u = 10\text{ mm/s} \\ h_c &= 5.00\text{ }\mu\text{m} \text{ for velocity } u = 100\text{ mm/s} \end{aligned}$$

and these differences in film thickness are clearly detected in the different levels of the focus error signal at position $x = 0$. Ripples were also present in these measurements, but are not shown.

Figure 9 Measured focus error signal versus the lateral position x at different values of the sliding velocity u (the contact load is 2 N)

Comparison with other methods

In part I the performance of focus error detection and its ability to measure surface profiles and roughness through a transparent layer on or near the scanned surface were discussed. Some measurements concerning the roughness deformation on contacting elastomers were presented above. The question may arise whether focus error detection is the most appropriate for this kind of measurements. This will now be discussed before the final conclusions on the method's ability are drawn. The results of the measurements and their practical importance for the understanding of the roughness deformation in the contact area are discussed elsewhere.⁴⁻⁷

The wet static contact

Alternatives to measuring the actual roughness texture of elastomers include several optical methods (interferometry, moiré, ellipsometry, light absorption, and fluorescence) and ultrasonic methods. Visscher⁴ discussed the applicability of these methods for the lubricated, dynamic contact situation, and most of his considerations also apply to the wet static contact situation. The same conclusions can therefore be drawn here.

Interferometry (see also part I under Optical profilometry¹), moiré, and ellipsometry can hardly or not be applied to surfaces with a roughness height on the order of $1\text{ }\mu\text{m}$, whereas absorption, fluorescence, and ultrasonic methods might be attractive but their accuracy is still questionable, especially for a lateral resolution on the order of $1\text{ }\mu\text{m}$. Therefore, we conclude that focus error detection is at present the most attractive method for these measurements.

The dry static contact

In the dry contact situation, focus error detection cannot be used to measure the total deformed roughness texture quantitatively. Only the real area of contact is determined. Considering the alternative methods mentioned above under the wet static contact section, interferometry, moiré, ellipsometry, and ultrasonic methods can in principle also be applied to the dry contact. However, their practical application for our situation is questionable for the same reasons as for the wet contact. Therefore, only the measurement of the real area of contact will be further considered in this section. This is also the main item in the literature on the dry static contact situation, and a brief review on this subject is given by Visscher⁴ and by Visscher and Struik.⁸ Woo and Thomas⁹ provided a more elaborate review, whereas Bhushan¹⁰ discussed the suitability of most methods, especially the electrical and optical, for application to magnetic tapes. He concluded that most methods are not suitable for magnetic tapes, and application of these methods to elastomers, as in our study, will also be hardly or not possible for the same reasons. Finally, two optical methods, interferometry and frustrated total internal reflection (FTIR), remained applicable.

Accuracy analysis of these methods, based on calculation of the irradiance distribution near the boundary of a real contact, showed that interferometry is more accurate than FTIR.

However, the elastomers in our application are much rougher than are magnetic tapes; therefore, interferometry is not suitable for us, as already discussed in part I.

Finally, we will compare focus error detection with FTIR. The inaccuracy in the evaluated value of the real area of contact measured by FTIR is caused by the optical tunnel effect, whereas the inaccuracy of the focus error method is primarily caused by interference. According to Bhushan,¹⁰ the optical tunnel effect yields more uncertainty in the real location of the contact boundary than does interference; therefore, focus error detection will be more accurate. The difference in accuracy will be especially significant for smaller slopes, when the uncertainty in the contact boundary location is larger than the spot diameter.

The lubricated dynamic contact

Visscher⁴ discussed the suitability of various methods for measurement of the lubricant film thickness on elastomers on a sufficiently small scale to detect the (possibly deformed) roughness texture of the elastomer during sliding motion. The methods considered were the mechanical, electrical (resistive as well as capacitive), magnetic induction, various optical, and ultrasonic methods. The suitability of the optical and ultrasonic methods was already mentioned above in the wet static contact section and the same conclusions apply to the dynamic contact.

Mechanical methods are not favored, mainly because of the fluid flow disturbance by the stylus in the contact area. Electrical resistive methods have a dynamic range limited to roughly 1 kHz, which is not sufficient. Otherwise, the required lateral resolution on the order of 1 μm cannot be realized using electrical capacitance techniques and probably not by magnetic induction methods. Obviously, electrical methods need the elastomeric counterface to be conducting, and magnetic induction needs a magnetic fluid or a magnetic counterface. This also limits the practical application of electrical and magnetic inductance techniques in our situation. Therefore, focus error detection is considered to be very attractive compared with other methods, when surface roughness effects in the lubrication of rough elastomers are to be studied.

Conclusions

The main conclusions, considering the use of focus error detection for scanning through a transparent

layer on or nearby the scanned surface, have been given in part I of this article and will not be recalled.

In this part, some applications were shown, considering both the static and the dynamic contact between a glass plate and an elastomeric specimen. Comparison with other methods yields the conclusion that focus error detection is attractive for these applications.

In addition to the conclusions of part I, it is worth mentioning that focus error detection is useful to measure the real area of contact in the dry contact situation, despite the fact that the deformed roughness texture itself cannot be determined.

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