NANO-SURFACE TEXTURE MEASUREMENT USING LASER INTERFEROMETRY AND IMAGE SYNTHESIS

Erik J. Salisbury, Kee S. Moon, and John W. Sutherland
Department of Mechanical Engineering and Engineering Mechanics
Michigan Technological University
Houghton, Michigan

ABSTRACT
Recently, surface measurement devices utilizing digital wave-front measuring interferometry interfaced with a computer system have been introduced and used in industry. These devices provide a non-destructive means by which the surface texture of a precision manufactured product can be measured at a several nanometer accuracy level. However, recent investigations show that the measurement accuracy of these systems is reduced seriously by systematic errors inherited from the measurement device. These systematic error sources include, roughness in the reference mirror, inaccuracy in the phase-shift, noise in the laser light source, extraneous light, etc. The deleterious effect of these errors have needs to be reduced, in order to improve the accuracy of the digital wave-front interferometry systems and thus enable the accurate measurement of nano-surfaces. In this paper, reducing the impact the systematic errors have on the surface texture measurement device is achieved based on a new technique that technique synthesizes multiple sets of surface data (fringe images) obtained by the digital wave-front measuring interferometry technique. This technique develops an improved set of phase-shift fringe images required to generate a surface topography. It is shown that the generated topography contains a smaller amount of systematic errors and therefore has improved accuracy.

CONVENTIONAL STYLUS BASED METHODS CAN NOT PROVIDE THE RESOLUTION NECESSARY FOR NANO-SURFACE MEASUREMENT AND ALSO MAY DAMAGE THE SURFACE BEING MEASURED. THEREFORE, A NON-DAMAGING OPTICAL METHOD CALLED LASER INTERFEROMETRY HAS THE POTENTIAL TO BE USED FOR HIGH ACCURACY NANO-SURFACE MEASUREMENT.

Interferometry has been studied for nearly 200 years, and is described in most undergraduate physics textbooks (Sears, et al., 1976). Interferometry produces an interference fringe pattern when two or more waves of light interact with each other. These fringe patterns can be analyzed to determine surface roughness. Ribbens (1969) and Motycka (1969) used the fringe contrast ratio, meaning the ratio of intensity between the fringes, to determine RMS (root mean square) roughness. Bennett (1976) calculated different characteristics of the surface including the RMS, by analyzing the undulations of the fringe lines.

The reconstruction of a specimen’s surface topography from fringe patterns has been accomplished by several different methods. Perry, et al. (1983) created a topographic map of the specimen using the undulations of the fringe lines. Bruning, et al. (1974) and Montgomery, et al. (1992) describe another method to obtain a topographic map of the surface using interference patterns. This method involves moving the reference mirror in small linear increments and storing the fringe pattern at each step. The phase shift of each point on the fringe relative to the central point is calculated and converted to a height, thus creating a topographic map of the surface. Moon, et al. (1993), describe a technique in which the surface topography data is determined from a single fringe pattern through a comparison of the actual fringe pattern with the fringe pattern of a perfectly smooth surface.

Among the optical interferometry techniques for precision surface measurement the digital wave-front measuring interferometry is a well-established technique and already used in industry (Bruning, et al., 1974, Montgomery, et al., 1992). In theory, this method allows accuracy of about 5 nanometers if a
laser is used as the light source. However, in practice, its accuracy is seriously reduced by the systematic errors embedded in the measurement system (Schwider et al., 1983). Under ideal conditions - i.e., perfect optical equipment, alignment of the equipment, phase shift movement, and laser beam source etc. - the topography generated from the technique would not include any distortion or error. The topography would, however, include distortion or error in it if any of the above conditions is not maintained. Therefore, in order to achieve higher accuracy required for the measurement of nano-surfaces, the effect of the error should be minimized.

This paper aims to provide a means to improve the accuracy of the digital wave-front measuring interferometry technique. The accuracy of the measurement is improved by obtaining enhanced phase-shift fringe images which contain a reduced amount of errors. The enhanced phase-shift fringe images are obtained by employing a new digital image synthesis technique (Moon and Sutherland, 1992). The technique synthesizes multiple sets of fringe images generated by the laser interferometry system. This technique, known as Procrustes analysis, develops a consensus set of phase-shift fringe images. The consensus fringe images contain smaller amounts of systematic errors than the original fringe images and provide a higher accuracy in the generation of surface topography.

**EXPERIMENTAL SETUP OF LASER INTERFEROMETRY SYSTEM**

The hardware elements of the interferometer system are shown in schematic form in Fig. 1. This interferometry system is a modified Twyman-Green interferometer. The light source is a low power He-Ne laser with a wavelength ($\lambda$) of 633nm. The laser beam is collimated and directed to the beam splitter where it is divided into two beams of equal intensity with one being transmitted into one arm of the interferometer and the other being reflected into the second arm. One beam reflects off the specimen while the other reflects off the reference mirror. They then return to the beam splitter, recombine and are directed to a CCD camera that is connected to an image processing unit. When the two beams recombine, a fringe pattern results that is due to the difference in the distance that the beams have traveled. The digitized image of the fringe pattern can then be accessed and analyzed.

As previously mentioned, a laser interferometer creates a fringe pattern that is caused by the difference in the distance traveled by the light in each arm of the interferometer. When the two light beams recombine at the beam splitter the phase difference of the two beams cause interference patterns. Consider two wave trains $E_1$ and $E_2$ that are shown in Fig. 1 and given by,

$$E_1 = I_0 \sin(\omega t)$$  \hspace{1cm} (1)
\[ E_2 = I_0 \sin (\omega t + \phi) \]  

where \( I_0 \) is the intensity of the light wave trains, \( \phi \) is the phase difference and \( \omega \) is the frequency of the wave. The phase difference \( \phi \) at a point is based on the variation in the height of the specimen surface, and any angle of tilt that may be present between the specimen and the reference mirror. If we neglect the tilt of the mirror, \( \phi \) can be represented by,

\[ \phi = \frac{4\pi h(x, y)}{\lambda} \]  

where \( h(x, y) \) is a represents the surface heights of the specimen. The wave \( E_0 \) is the wave that results from the combination of waves \( E_1 \) and \( E_2 \).

\[ E_p = E_1 + E_2 \]

The energy flux or intensity \( I \) of a wave is proportional to the square of the amplitude of the wave field, so the resultant intensity of \( E_p \) can be called \( I \) and be written,

\[ I = 2K I_0 \left[ 1 + \cos \left( \frac{4\pi}{\lambda} h(x, y) + \delta \phi \right) \right] \]

where \( K \) is a constant and the term \( \delta \phi \) is a phase change introduced into one of the optical paths to help in the reconstruction of surface topography.

By using a linear actuator to produce the phase change term \( \delta \phi \), and by obtaining the intensity value of the cosine wave at the phase change points, the surface topography can be obtained. For instance, three phase-shifts corresponding to a \( \delta \phi \) of -120°, 0°, and 120° result in three intensity values \( I_1 \), \( I_2 \) and \( I_3 \) which can be described by,

\[ I_1 = C [1 + \cos (\phi - 120^\circ)] \]

\[ I_2 = C [1 + \cos (\phi)] \]

\[ I_3 = C [1 + \cos (\phi + 120^\circ)] \]

where \( C \) is a constant (Montgomery, et al, 1992). Using these three equations the height \( h(x, y) \) can be determined by,

\[ h(x, y) = \frac{\lambda}{4\pi} \tan^{-1} \left( \frac{-2^{1/2} (I_1 - I_3)}{2I_2 - I_1 - I_3} \right) \]

The solution of \( \tan^{-1}() \) contains values between \(-\pi/2\) and \(\pi/2\), a discontinuity exists for every phase change of \( \pi \) or correspondingly every change in height of \( \pi/4 \) or 158.25nm. The result is represented as a saw tooth profile. A simple algorithm is used to eliminate the discontinuity of the saw tooth profile and reconstruct the desired profile. Finally, a least squares plane is fit to the surface data to remove the effect that a tilted reference mirror may have imparted onto the surface. Note that the generated topographic map may contain a significant amount of error in it. In other words, the map may not show the actual surface texture of the product. The error can be due to systematic errors of the measurement system originating from imperfect optical equipment, alignment of the equipment, reference phase change by actuation, noise in laser beam source, etc. This paper describes a new technique to reduce the impact of the systematic errors on the accuracy of the measurement and will be described in the following section.

**IMPROVEMENT OF MEASURED ACCURACY VIA IMAGE SYNTHESIS**

As mentioned before, digital wave-front measuring interferometry is a well-established technique and is already used in industry to measure precise surfaces. In theory, this method may allow resolution of about 5 nm under near perfect measurement conditions when a laser is used as the light source. However, in practice, its accuracy and resolution are seriously reduced by the systematic errors embedded in the measurement system (Schwider et al., 1983).

The accuracy and resolution of the technique depend heavily on accurate phase-shifts measured by the intensity values of the interferometry fringe images. Inaccuracies in the phase-shift caused by imperfect optical equipment (i.e., roughness in reference mirror, lenses, etc.), inaccurate movement and positioning of the mirror by the actuator, and noise in the laser beam source would introduce the phase shift error. Hence, the obtained topography would include serious distortion or errors in it. For example, Fig. 2 shows four different sets of simulated fringe images. Each set of fringe images \( I_1 \), \( I_2 \) and \( I_3 \) would provide a perfectly flat surface (straight line in cross-sectional profile) if there is no error in the intensity values of the fringe images. Several different types of errors were simulated and their effect on the surface topography were tested. From the figure, it is evident that the error and noise in each set of the fringe images cause a serious distortion in the generated surface topography. Therefore, it is evident that the effect of the distortion or error on generating surface topography must be minimized in order to achieve higher accuracy and resolution required for the measurement of nano-surfaces.

This paper describes a new technique (Procrustes analysis) which develops a set of enhanced fringe images from multiple sets of raw fringe images. The distortion or error, which affects the accuracy of a measurement system, is minimized in the enhanced fringe images. The soundness of the technique has already been tested and demonstrated by the authors for sensor and image synthesis applications (Sutherland and Moon, 1992, Moon and Sutherland, 1992). In short, the technique combines and manipulates sets of data to reach a consensus. It is expected that the resulting surface topography will have an improved accuracy and resolution.

Procrustes analysis finds its roots in the sensory science field (Gower, 1975; Hurley and Catell, 1962; Kristof and Wingersky, 1971; TenBerge, 1977) and has recently been applied to the characterization of food products (Gower, 1975; Oreskovich et al., 1991), sensor integration in manufacturing processes (Sutherland and Moon, 1992) and image synthesis (Moon and Sutherland, 1992).
FIGURE 2: SIMULATED PHASE-SHIFT FRINGE IMAGES AND GENERATED SURFACES (CROSS-SECTIONAL PROFILES)
FIGURE 3: ENHANCED FRINGE IMAGES AND IMPROVED ACCURACY IN THE SURFACE RECONSTRUCTION

FIGURE 4: EXPERIMENTALLY OBTAINED FRINGE SETS
Suppose that $m$ phase-shift fringe images are required to generate the topography of an object. Let $X_i$ be a matrix containing $m$ fringe image intensity data. For example, the fringe images from Fig. 2 can define four $X_i$'s ($n=4$) and three phase-shifts ($m = 3$). The purpose of Procrustes analysis is to search for the transformations that will reduce the sum of squares or, equivalently, produce a greater amount of agreement between the four $X_i$'s. In other words, the Procrustes analysis tries to obtain an agreement for the four $X_i$'s through translation, rotation, and scaling transformations. The rotation of $X_i$ may be accomplished by post-multiplying the matrix by an orthogonal rotation matrix, $H_i$. Uniform scaling may be accomplished by multiplying $X_i$ by the scalar $p_i$. Translation may be accomplished by adding the same row vector to each row in $X_i$, or equivalently by adding the matrix $T_i$ to $X_i$, where $T_i$ contains $n$ identical row vectors. When the translation, rotation, and scaling transformations are applied to $X_i$ they produce a new matrix,

$$X_i' = p_i \cdot X_i H_i + T_i \quad (10)$$

The Procrustes problem is then to select $p_i$, $H_i$, and $T_i$ ($i = 1, 2, ..., m$) so that the residual sum of squares is a minimum.

$$S = \sum_{i<j}^{m} \left\{ (p_i \cdot X_i' H_i + T_i) - (p_j \cdot X_j' H_j + T_j) \right\}$$

$$- \left[ (p_i \cdot X_i' H_i + T_i) - (p_j \cdot X_j' H_j + T_j) \right]' \quad (11)$$

Differentiating Eq. (11) with respect to this translation term and then equating the result to zero gives the result that all $m$ data sets should be translated to have the same centroid. This centroid may be conveniently chosen to be the origin. To accomplish this translation, the matrix $T_i$, consisting of $n$ identical row vectors, may be formed. A column element in $T_i$ is simply the negative of the column mean of $X_i$.

With respect to the selection of the rotation matrices, $H_i$, it may be noted that since $S$ will be unaffected by orthogonal rotations of the whole system of points (i.e., the points for all images), no unique solution for $H_i$ can be found. To obtain a solution, one might consider determining the rotation matrices relative to a fixed data set (e.g., $X_1$). Such a scheme would produce only $m-1$ rotation matrices. In this paper, however, a solution that produces $m$ rotation matrices will be used.

To find the best fit rotation matrix, the Lagrangian of Eq. (11) may be differentiated with respect to the rotation matrix, the result set equal to zero, and the best fit rotation matrix, $H_i$, solved for. The Lagrange multiplier is used to minimize the equation where the variables are subjected to a constraint equation. In this case the constraints ensure a valid rotation matrix. Doing this gives:

$$H_i = (X_i'Y'X_i')^{-1/2}X_i'Y \quad (12)$$

where, $Y = \frac{1}{m} \sum_{i=1}^{m} p_i X_i H_i$.

Note that $Y$ is the consensus, i.e., the matrix containing the centroid points.

To find the square root of $(X_i'Y'X_i)^{-1}$, we may express it as $V_i E_i V_i^{-1}$, where $E_i$ is a diagonal matrix containing the eigenvalues and $V_i$ contains the eigenvectors of $(X_i'Y'X_i)^{-1}$. The square root of $(X_i'Y'X_i)^{-1}$ may then be expressed as $(V_i E_i^{1/2} V_i^{-1})$ where $E_i^{1/2}$ is obtained by taking the square root of each element on the diagonal of $E_i$. Thus, the best fit rotation matrix is given by:

$$H_i = V_i E_i^{1/2} V_i^{-1} X_i'Y' \quad (13)$$

To find the best fit scaling factor, the Lagrangian of Eq. (11) may be differentiated with respect to $p_i$, the result set equal to zero, and the best fit scaling factor solved for. The Lagrange multiplier in this case constrains $p_i$ to being non-zero. Doing this gives:

$$tr(X_i' H_i Y') = \frac{1}{m} \sum_{i=1}^{m} tr(X_i X_i')$$

$$\rho_i = \frac{\sum_{i=1}^{m} tr(X_i X_i')}{m tr(YY') tr(X_i X_i')} \quad (14)$$

As was the case with the solution for the best fit rotation matrix, the expression for the best fit scaling coefficient, Eq. (14), does not provide a closed form solution for $\rho_i$. These expressions, however, may be used in an iterative fashion through a Procrustes algorithm. See Moon and Sutherland (1992) for a detailed explanation of the algorithm.

The iterative algorithm to select the optimal values of $p_i$, $H_i$, and $T_i$ ($i = 1, 2, ..., m$) has been developed and tested for the simulated examples shown in Fig. 2. Figure 3 shows a consensus set of the three phase-shift fringe images and a generated surface topography (cross-sectional profile). From Fig. 3, it is apparent that the Procrustes analysis technique provided a reconstructed surface that has a smaller amount of error than each individual case, as shown in Fig. 2, and for the average of the four cases as shown in Fig. 3. This simulation example has shown that the Procrustes analysis technique can provide improved accuracy of the digital wave-front measuring interferometry devices over conventional averaging of surface heights. The use of Procrustes analysis for measurement error reduction and system accuracy improvement for experimentally obtained interferometry data will be demonstrated in the following section.

**EXPERIMENT**

The previous section contained a simulation example in which the consensus surface profile was obtained using four data sets with each set containing three two-dimensional fringe patterns. In this section, the results of an experimental study will be presented.

The laser interferometer setup as shown in Fig. 1, with a precision ground computer hard disk as the specimen, is used to obtain four sets of fringes with each set containing three fringe patterns as shown in Fig. 5. The axis labels for the fringe patterns in Fig. 5 are pixels. Each set of fringes were gathered at a random starting point on the actuators, at a different spot on the reference mirror and with the aperture setting on the camera randomly adjusted so that each set of fringes has a different brightness. These adjustments are made because it is not known which setting is the best case. For each set of fringes a topographic map is
constructed using Eq (9) with a pixel spacing of 4.2 μm in both the horizontal and vertical directions, the resulting surface maps are shown in Fig. (5).

By comparing the topographic maps in Fig. 5, it is evident that they are not the same. For example, the topographic map #2 contains a number of tall peaks. However, the other maps do not indicate these same peaks. Therefore, it might be concluded that these large peaks present in map #2 are likely due to the presence of noise in the system, possibly due to extraneous light in the interferometer due to dust or a dirty optical component. Additionally, in examining each of the four topographic maps of Fig. 5, a wave travelling along the x-axis at a frequency twice the fringe spacing frequency can be identified. In fact, this frequency may be due to errors in the phase change, δφ, which can be caused by an imperfect actuator (Schwider, et al., 1983). Table 1 shows the 3-D surface roughness parameters Rq and Rmax for each of the four topographic maps. The value of Rq ranges from 12.53nm to 17.96nm and the values of Rmax range from 125.16nm to 294.82nm. This large range in the roughness parameters indicates that a significant amount of measurement error is effecting the accuracy of the surface topography reconstruction.

The Procrustes algorithm described previously will be used in an attempt to reduce the sources of error present in the digital wavefront interferometry system. Considering that the number of phase shift fringe patterns in each fringe set is three (m=3), and the number of sets is four (n=4), there are four X_i's, where each X_i is a matrix that contains m columns with each column containing the intensity values in each of a fringe pattern entered rowwise. These X_i's are input into the Procrustes algorithm and a set of consensus fringe patterns is output. These consensus fringe patterns are shown in Fig. 6.

Figure 7 shows a topographic map obtained by averaging the four sets of surface data shown in Fig. 5 along with the topographic map reconstructed from the consensus fringe patterns shown in Fig. 6. Table 1 shows that both the averaged surface (Rq=11.82nm and Rmax=112.75nm) and the surface obtained by using Procrustes analysis (Rq=10.82nm and Rmax=104.59nm) have roughness values that are smaller that the initial surfaces, however the Procrustes technique has reduced the roughness values by a greater amount. This reduced roughness may be a result of reducing the amount of measurement accuracy. Also, the extraneous frequency at twice the fringe spacing can not be seen in Fig. 7 indicating that the deleterious effect that inaccuracies of the phase shift have on the reconstructed surface have been reduced. These results have shown that Procrustes analysis provides a surface reconstruction with a smaller amount of error thus...
resulting in a more accurate representation of the specimens surface topography.

SUMMARY AND CONCLUSIONS

This paper has presented a new method (Procrustes analysis) to improve the accuracy of digital wavefront interferometry systems. Initially a description of the interferometry system and surface reconstruction technique was presented. Then a description of the Procrustes analysis algorithm, which attempts to develop an enhanced set of fringe patterns from a multiple set of raw fringe patterns, through translation, rotation and scaling transformations, was given. A simulation example, in which the Procrustes analysis algorithm was shown to provide greater accuracy, was then demonstrated. Finally, the Procrustes analysis algorithm was applied to a set of experimentally obtained fringe patterns, and the resulting consensus topographic map was compared to the raw topographic maps and an average of the raw topographic maps.

It has been shown that the effect of errors on the accuracy of digital wavefront measuring interferometry systems can be reduced by using the Procrustes analysis algorithm. This result may provide the capability to increase the accuracy of these systems to better than 5 nm, and provide engineers the ability to measure and assess surfaces with smaller roughness than is now possible. Future work includes determining what type of data sets provide the best results.

REFERENCES


