Development of a Microscopic Laser Interferometry System for Precision Surface Measurement

A new technique for the evaluation of precision surfaces using laser interferometry is presented. Laser interferometry creates a fringe pattern which contains information about the surface texture of the specimen. The technique presented compares the ideal fringe pattern to the actual fringe pattern to determine the height deviation on the specimen. In this paper, a simulation model is used to predict the fringe pattern for a given surface. The surface topography of a groove on a computer hard disk is then reconstructed from an experimentally obtained fringe pattern. The reconstruction process is verified by comparing the reconstructed surface to a photograph of the actual surface.

1 Introduction
The surface texture of manufactured parts is of tremendous importance in precision engineering. Although technologies and processes are becoming more widely available for the production of precision surfaces, very little equipment and methodologies are available for assessing the quality of precision manufactured surfaces. The increasing emphasis on precision engineering has therefore necessitated the development of instrumentation and methodologies for the measurement and the improvement of precision manufactured surfaces.

Interferometry is a technique which can provide a method for evaluating precision manufactured surfaces. Interferometry is the study of the interference of light. When two or more light waves cross each other they interfere. This means, not that they block the other's progress, but that they combine. The combination of separate waves of light creates an interference pattern (fringes) which is the intensity distribution of the combined light waves. To obtain observable interference patterns, the sources of light must produce waves which are in phase at the start. This property is called coherence and is obtained by splitting the light from one source, directing it on different paths, and then recombining it at a point to produce interference patterns. By controlling the path of the light waves, an interferometer can be constructed to perform a useful service.

Interferometry has been utilized to measure the characteristics of manufactured surfaces for years. It is well known that for flat specimens the reflected out-of-phase light waves produce a fringe pattern consisting of parallel and equally spaced light and dark bands. Adding texture to such a flat surface causes undulations on the fringe lines where, the undulations mimic the texture of the surface. Rolt (1956) and Poole and Dowell (1960) used these properties for determining the accuracy, including height and flatness, of gauge blocks. Bennett (1976) calculated different characteristics of the surface including the RMS, by analyzing the fringe lines. Ribbens (1969) and Motycka (1969) used the fringe contrast ratio to determine RMS roughness. Perry et al. (1983) created a topographic map of the specimen using these parallel fringe lines; however, this method gives poor planar resolution because it is only possible to have as many traces as there are dark fringe lines and is difficult to automate.

Bruning et al. (1974) and Montgomery et al. (1992) describe another method to obtain a topographic map of the surface using interference patterns which is used in the commercially available interferometers (WYCO, ZYGO). This method involves moving the reference mirror in small linear increments. The fringe pattern is captured for each movement and stored. The intensity at each of the sampling points varies sinusoidally as the reference is moved linearly. The phase shift of each point on the fringe relative to a central point is calculated and converted to a height, thus creating a topographic map of the surface. The method discussed by Bruning et al. (1974) requires the capturing of up to one hundred separate fringe patterns, while the technique presented by Montgomery et al. (1992) requires three fringe patterns. These methods are time consuming and require an actuator that has an accuracy of several nanometers.

The surface measurement method presented in this paper builds on the work of Perry et al. (1983) in that only one fringe pattern is needed to determine the topographic map of the surface; however, unlike the work of Perry et al. (1983) a surface height can be calculated at each pixel position in the fringe image. This is accomplished by comparing the ideal fringe pattern to the actual fringe pattern to determine the height deviation on the specimen surface. Therefore, a complete topographic map can be constructed without the need for a highly accurate actuator as required by Bruning et al. (1974) and Montgomery et al. (1992).

This paper describes and evaluates an interferometry-based surface measurement technique that automates and computerizes the work that people have done visually in the past using instruments such as the Zeiss interference microscope. This technique includes a combination of hardware and software for measuring manufactured surfaces. Included in the hardware is a microscopic laser interferometer coupled with a machine vision system to obtain a fringe image for the surface of interest. The software includes data acquisition, image processing, and a simulation model which not only allows for the reconstruction of a surface from a fringe pattern, but also provides the ability to estimate the appearance of a fringe pattern given any surface. In this paper, a method is developed for determining the topographic map from a single fringe image by using the intensity value at each pixel in the image. The method is validated using simulation which both predicts the fringe image from a surface and recreates a surface from a fringe image. A comparison between a surface reconstructed from a fringe image and a photograph of the same surface is also made.

The remainder of the paper consists of four sections. The first section contains a description of the hardware of the microscopic laser interferometer along with an explanation of the
### Table 1 Equipment for microscopic laser interferometer

<table>
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<th>He-Ne Low Power Laser</th>
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<td>Various Optics</td>
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A physical mechanism behind interferometry. The simulation model and the relationship between the surface and predicted fringe intensity level is then described. The method for generating a surface map from an experimentally obtained fringe image is described along with a discussion of the system performance and an example presented. Finally, discussion of the results in this paper will be presented and some conclusions made.

## 2 Laser Interferometer System

The hardware elements of the interferometer system are listed in Table 1. These elements were assembled to form a complete system as displayed 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 of 637 nm. The laser beam is collimated and directed to the beam splitter where it is divided into beams of equal intensity with one being transmitted into one arm of the interferometer and one 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 caused by the difference in the distance that the beams 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 given by,

$$E_1(x, y) = \sqrt{I_0} e^{2i\phi}$$

$$E_2(x, y) = \sqrt{I_0} e^{2i\phi(x,y)}$$

and shown in Fig. 1, where $I_0$ denotes the wavefront amplitudes, $k = 2\pi/\lambda$ is the wave number with $\lambda$ equal to the wavelength of the light, and $\phi$ is the phase difference (Bruning et al., 1974). The phase difference $\phi$ at a point is based on the variation in the height of the specimen surface, and the angle of tilt, $\alpha$, of the reference mirror. If we consider an ideal specimen (perfectly flat), the angle $\alpha$ affects $\phi$ such that,

$$\phi = \frac{4\pi x \tan(\alpha)}{\lambda}$$

where from Fig. 1 it can be seen that $x$ is the distance along the mirror in the $x$-direction. These two waves join at the beam splitter and the wave $E_3$ that results from the superposition of waves $E_1$ and $E_2$ is (Brown, 1965),

$$E_3(x, y) = E_1(x, y) + E_2(x, y).$$

The energy flux or intensity $I$ of a wave is proportional to the
square of the amplitude of the wave field, or $E_y E_y^*$ where $E_y^*$ is the complex conjugate of $E_y$. From this, the intensity distribution in the interference pattern is (Bruning et al., 1974),

$$ I(x, y) = 2L_0(1 + \cos(\phi(x, y))). $$

(5)

It is obvious that the intensity fluctuates as a cosine function of $\phi$. Therefore, when the surface of the specimen is flat and the reference mirror is tilted by an angle $\alpha$ as shown in Fig. 1, as $x$ increases, $\phi$ increases linearly. This linear increase in $\phi$ causes the intensities in the $x$-direction to vary sinusoidally, meaning that the intensity distribution in the fringe pattern along the $x$-direction varies as a cosine.

When the surface of the specimen is not ideal, but contains variation represented by $w(x, y)$ as shown in Fig. 1, the phase angle becomes a function of two variables,

$$ \phi = \frac{4\pi}{\lambda}(w(x, y) + x \tan(\alpha)). $$

(6)

The reference mirror is assumed to be tilted only in the $x$-direction. In this case, considering the intensity values in the $x$-direction for a given $y$ value, the intensities are affected both by the angle of the reference mirror and the undulations on the surface of the specimen. The term $x \tan \alpha$ will cause the intensities along the $x$ direction to vary as a cosine, while the surface deviations $w(x, y)$ will introduce a variation from this ideal cosine.

The experimental microscopic laser interferometer system applies a tilted reference mirror that would generate a straight and parallel fringe pattern for an ideal surface. Due to the underlying nature of precision surfaces, their resultant fringe patterns consist of nearly straight and parallel fringes. The difference between the intensity distribution of an ideal fringe pattern and the intensity distribution of an actual fringe pattern can be converted into surface deviations. Once the surface deviations are known, a topographical map of the surface can be plotted.

3 Simulation

To accomplish the reconstruction of a surface topography from a fringe image by comparing the intensities in the ideal fringe pattern with the intensities of the actual fringe pattern requires the ability to generate the fringe pattern for an ideal surface. A simulation model was developed that provides a relationship between the surface texture and the resulting interference pattern. The simulation model can be used to predict the interference fringe image for the ideal surface with no defects, and the fringe images for surfaces with various defect patterns. The actual fringe image of a sampled surface can then be compared to the patterns predicted by the model, and the type of defect embedded in the surface can be analyzed. Combining Eqs. (5) and (6) yields

$$ I(x, y) = 2L_0(1 + \cos\left(\frac{4\pi}{\lambda}(w(x, y) + x \tan(\alpha))\right)). $$

(7)

To simplify calculations the intensities are normalized with the result being.

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Fig. 4 Fringe pattern for surface in Fig. 3

Fig. 5 Normalized intensity values for one line of pixels from Fig. 4

Fig. 6 Flat surface with added noise (height axis: 1 tic = 0.02 $\mu$m)

Fig. 7 Simulated fringe pattern of flat surface with noise

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\[ I_{\text{norm}}(x, y) = \frac{1 + \cos \left( \frac{4\pi}{\lambda} \left[ w(x, y) + x \tan(\alpha) \right] \right)}{2} \] (8)

A flow chart of the simulation process to create the fringe pattern from a surface is shown in Fig. 2. The surface generation module has three inputs, the ideal (flat) surface, height variation noise, and the defect chosen to introduce on the surface. The surface generation module outputs the surface topography into the phase angle difference calculation routine. Also input to this routine is an estimate of \( \alpha \) depending on the desired spacing of the fringe lines. The routine calculates the phase angle for each pixel and outputs the phase angle into the fringe intensity calculation routine. The routine calculates what the normalized intensity at each pixel is from the phase angle [Eq. (8)] and outputs the intensity matrix to the image construction module. Here the intensity matrix is scaled from 0–255 and the resultant fringe image can be printed.

Following are three examples of the simulation model. First the model is run using the ideal flat surface, then noise is added to the surface, and finally a defect is added. Figure 3 shows a perfectly flat surface that can be considered the ideal surface for a precision manufactured component. The interference pattern from this surface should reveal fringe lines that are perfectly straight and evenly spaced. The interference fringe pattern predicted by the simulation model is shown in Fig. 4 and reveals straight evenly spaced fringe lines as expected. The normalized intensity levels from a single line of pixels perpendicular to the fringe lines in Fig. 4 is shown in Fig. 5. It is evident that the intensities vary in a sinusoidal manner as predicted when \( w(x, y) \) is constant.

It is impossible to manufacture a perfectly flat surface, therefore even precision manufactured surfaces contain some variation. This variation is modelled by adding a normal deviate \( N(0, 0.001 \text{ \mu m}^2) \) to the surface shown in Fig. 3, with the resulting surface shown in Fig. 6. The fringe pattern predicted by the simulation model is shown in Fig. 7. It is evident that there exists a similarity between Figs. 4 and 7. Both contain straight and equally spaced fringes; however, as expected the variation added to the ideal flat surface has introduced noise to the fringe pattern.

The added noise is evident from a comparison of Fig. 8, a single pixel line perpendicular to the fringe lines in Fig. 7, with Fig. 5 obtained from the ideal flat surface. Figure 8 appears as a cosine wave with added noise.

Defects present on the surface of a manufactured part may compromise its ability to perform its intended function. Therefore, it is important to have the ability to assess the quality of the surface of a part and determine if there are defects present. Figure 9 gives a representation of a defect that may be found on a precision manufactured surface. Shown is a shallow groove or scratch present on a surface similar to Fig. 6. The interference fringe pattern should indicate this groove, and Fig. 10, the fringe pattern for this surface generated by the simulation model has fringe lines that have a curvature associated with them. This curvature of the fringe lines is produced by the curvature of the groove. Figure 11 displays a single pixel line and appears similar to that of Fig. 8 as expected. The fringe lines shown in Fig. 10 were generated perpendicular to the curvature of Fig. 9 and
therefore have no effect on the intensities for a single line of pixels parallel to the curvature.

The simulation model has shown the ability to accurately estimate the appearance of the fringe pattern from a given surface. The next step is to use the model to reconstruct the actual surface structure from a fringe pattern.

4 Surface Reconstruction

The process of surface reconstruction is the inverse of the simulation model. From Eq. (8) it can be determined that,

\[ w(x, y) = \frac{\lambda}{4\pi} \arccos (2I_{\text{norm}}(x, y) - 1) - x \tan \alpha \]  

(9)

This equation can be thought of as similar to a 3-D stylus instrument that takes multiple parallel traces to measure the surface topography. This system is like taking multiple 2-D traces with each trace occurring perpendicular to the fringes and putting all the 2-D traces side by side to build a 3-D surface topography.

The measurement resolution in the lateral directions (X and Y) depend only on the selection of the collimating and magnifying lenses. Depending on the selection of these lenses it is possible to evaluate both large (7 cm²) and small (0.2 mm²) surface areas depending on the desired result. The resolution in the height direction is a function of the wavelength \( \lambda = 632.8 \) nm and the intensity range available in the image acquisition equipment (0–255). Therefore, because a distance of \( \lambda/4 \) or 158.2 nm will translate to the maximum intensity change in the fringe,

\[ \text{resolution} = \frac{\lambda/4}{\text{max} (I) - \text{min} (I)} = \frac{158.2}{256} = 0.618 \text{ nm} \]  

(10)

This means that a change of 0.618 nm in height on the specimen will cause a change in the intensity of a pixel by 1.

This surface reconstruction equation is based on the assumptions that laser light source is error free, the intensity of the beam reflected from the reference mirror and the specimen is constant, the angle of the reference mirror tilt is known, and the reference mirror is perfectly flat. Any deviation from these assumptions introduces error into the reconstruction algorithm and decreases the accuracy of the system.

The laser is frequency stabilized with coherence lengths greater than 6 m and will have little effect on the system accuracy. The reference mirror is smooth enough \( Ra = 0.274 \) nm so that it also will have little effect on the system. The reference mirror angle of tilt can be accurately measured by determining the distance between dark bands in the fringe image. The assumption that introduces the greatest amount of measurement error into the system is that of constant intensity of the light reflecting off the reference mirror and the surface.

This constant intensity is represented in Eq. (1) and (2) by \( \sqrt{I_0} \). By taking images of the beam reflected from each of the surfaces individually and constructing a histogram it was determined that \( I_0 \approx N(\mu_0, \sigma_0^2) \). When the two beams \( E_1 \) and \( E_2 \) combine to form \( E' \) assuming that each beam is of the same phase, the intensity distribution is \( I = N(2\mu_0, 4\sigma_0^2) \) from Eq. (5). Since a deviation from the constant intensity causes a deviation in the measured height it is the variance of \( I \) that affects the measurement accuracy. Since the amount of scattered vs. reflected light increases as surface roughness increases, rougher surfaces will cause more deviations from a constant intensity beam resulting in a larger measurement error. Also, as with any interferometry based surface measuring device, the system is only accurate if there are no height deviations greater than \( \lambda/2 = 316.4 \) nm at consecutive sampling intervals.

An example of the surface reconstruction equation is now presented. Figure 12 shows an actual interference fringe pattern obtained from the surface of a computer hard disk. It is evident from the fluctuation of the fringe lines that the hard disk is not ideally flat and that there exists a surface topography. The topographic map reconstructed from the fringe pattern using Eq. (9) is shown in Fig. 13.

The optics were chosen to provide a lateral resolution of 0.5 \( \mu m \) in the X and Y directions, and the imaging system was set to allow the maximum range of intensities giving resolution in the height direction of 0.618 nm. The reference beam and the specimen beam were imaged separately and two histograms were constructed to validate the assumption of normality. The

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**Fig. 13** Reconstructed 3-D surface topography

**Fig. 14** Normalized intensity values for one line of pixels from Fig. 12

variance of the initial intensity was calculated to be $\sigma_i^2 = 17.7$. From this, the variance of the combined intensity was determined to be $\sigma_f^2 = 70.9$. Therefore, 90 percent of the intensities are within $\pm 13$ of the nominal with 95 percent falling within $\pm 16$ of the nominal. From Eq. (10) it can be determined that a change in intensity of 1 yields a surface height of 0.618 nm, therefore 90 percent of the surface heights have an error smaller than $\pm 8.53$ nm with 95 percent being smaller $\pm 10.2$ nm.

The most obvious feature present in the topographic map of Fig. 13 is the existence of feed marks from the face turning process that was used to manufacture the disk. A secondary feature that has been indicated on the figure is the presence of a shallow groove similar to the one shown in Fig. 9. Due to the similarity of the surfaces in Figs. 13 and 9, there should exist a similarity between the fringe patterns of the surfaces. A comparison of Figs. 12 and 10 reveal that this is the case, both fringe patterns consist of fringe lines with similar curvature. The feed marks present in Fig. 13 are not evident in Fig. 12, but are captured by the reconstruction process. This would not happen using the reconstruction method of Bennett (1976) and Perry et al. (1983). A single pixel line from Fig. 12 is given in Fig. 14. It is apparent that the same periodic function of intensities exists for the actual surface as for the simulated surfaces.

In an attempt to verify the surface reconstruction a photograph of the groove on the hard disk was taken and is shown in Fig. 15. The approximate measurement area as shown in Fig. 13 is indicated by a box in Fig. 15. It is impractical to measure this surface using a conventional stylus instrument because the resolution is several orders of magnitude too large. From Fig. 15 the feedmarks on the surface from the face turning operation are readily apparent and it can be determined that the surface reconstructed from the fringe pattern is accurate.

5 Summary and Conclusions

A system to reconstruct a surface from a fringe pattern by comparison of an ideal fringe pattern with an actual fringe pattern was developed. This method is capable of predicting the fringe pattern for a given surface. The method was validated through simulation and by comparing a reconstructed surface with a photograph of the same surface.

The surface reconstruction method calculates the height of the surface at each pixel by comparing the intensity of the experimental fringe pattern at that pixel with the intensity of the ideal fringe pattern at that pixel. Therefore, unlike other interferometer surface reconstruction techniques it does not depend on the distortion of the fringe lines to calculate the height of the surface. This is important, because if a surface is flat with only random height variations the fringe lines will be straight. Therefore, the calculation based on the slope of the fringe lines will yield a flat surface, whereas the intensity comparison method utilized here will capture the height deviations. Another benefit is that only one fringe image is needed, unlike the phase shift interferometry method used in commercially available interferometers which requires a minimum of three fringe images and an actuator with nanometer resolution.

The accuracy of the system (approx. 8 nm) compares well with that of the interferometers using the phase shift technique of Bruning et al. (1974) where the accuracy was reported to be $\lambda/100$ which equals 6.32 nm using the He-Ne laser as a light source.

This technique provides an effective method for the assessment of precision manufactured surfaces. Having a means avail-

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**Fig. 15** Microscopic photograph of groove in computer hard disk (1 tic equals 40 μm)

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7 References


