3-D laser metrology for the assessment of curved surfaces
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Abstract

Measurement instruments are identified which are suitable for the assessment of curved samples typically used in the manufacture of lens technology. The advantages and limitations of each instrument are discussed, together with their suitability for measuring surfaces and producing data that can be analysed for sphericity information. A number of numerical sphere-fitting algorithms are suggested for radius of curvature analysis, and a Contour Analysis technique is developed for the assessment of errors of Form without the need to sphere-fit to the data. Contour Analysis is shown as a useful visualisation tool, allowing the user to clearly see surface distortions, such as astigmatism, without the need to interpret the deviation from sphere plots.

1. Introduction

In recent years there has been a move towards 3-D surface metrology; the full analysis of a surface providing the user with more detailed information than available from the traditional 2-D techniques. Examples of the additional information that can be obtained from 3-D data sets are the orientation of surface features, the "lay" of the surface, or volume analysis for erosion calculations, [1].

In an attempt to avoid the "parameter rash" seen in 2-D measurement, and described by Whitehouse, [2], research has been undertaken to define guidelines by which 3-D measurements should be made. Such guidelines are
presented by Dong et al, [3-6], together with a number of suggested Parameters for characterisation of surface topography. The surface parameters presented in the studies are calculated after the removal of a reference surface from the 3-D surface profile. Traditionally this reference surface was a least-squares plane, [3]; more recently, Stout et al. [7], have suggested a number of alternatives, including spheres, polynomials and cylinder-fits.

Surface topography parameters can provide much useful information about the sample, but in many cases the overall shape of the object, its Form, is equally as important. This paper presents research about 3-D Form measurements, with particular emphasis being placed on the use of spheres and circles as the reference surfaces. The dimensions of these best-fit reference surfaces can be compared to the nominal dimensions of the surface, allowing manufacturing tolerances to be assessed and tooling to be adjusted if necessary. Furthermore, by removing the reference surface from the data, the deviations of the sample from its nominal shape, the Errors of Form, can be observed. These provide useful information about the quality of a component.

Measuring curved surfaces presents a range of new problems to the measurement instruments. These problems are addressed, and a number of Laser-based measurement instruments suitable for the assessment of curved surfaces identified. Several numerical techniques are then offered which can be used to analyse the data from some of these instruments, allowing the errors of Form to be evaluated. Finally, an alternative numerical technique is presented, which allows the errors of Form to be observed.

2. Instrumentation Systems

For the precision measurement of 3-D Form, the metrology of the problem needs careful definition since this will depend fundamentally upon the scale or physical dimensions of the measurement. In this case, the application is to curved surfaces of approximately 10mm by 10mm (x,y axes), with a typical application being quality control for contact lens manufacturing components.

The main criteria for these measurements is the tolerance of the radius of curvature of the best-fit reference surface to the measurement’s data set. Lens’ tolerances require that the radius of curvature can be found to ±10μm in order that the lens can be categorised into its correct power band, i.e. with ±0.125 Dioptre, [8]. This places considerable pressure on the resolution and accuracy of all axes of the instrument.

A further criteria is the gauge range of the instrument; the maximum height range that the system can measure. Figure 1 shows a 2-D curved surface of radius, r_c. It can be shown that the maximum measurement length, d, is a function of the radius of curvature, r_c, and the gauge range, g, where;
A number of instruments have been identified which meet the above criteria; these are detailed below. Generally, these instruments map the surface, providing Cartesian data on the surface in x, y, and z coordinates. Once this data is obtained, it is then necessary to analyse its radius of curvature using a numerical algorithm.

\[ d = 2\sqrt{2rg - g^2} \]  \hspace{1cm} (1)

2.1 Laser Ranging Non-Contact Probes

A precision table system will move the sample under the probe in the (x, y) axes, allowing height data to be gathered about points on the surface lying on a fixed grid. The probes range-find using either an auto-focusing, or triangulation technique.

The auto-focus probe makes use of a Laser with adjustable optics. A 1\(\mu\)m spot is projected onto a surface, and the quality of focus of the reflected beam considered by a photo-diode array. A servo-system, attached to the objective lens, adjusts the position of this lens for best focus. By monitoring the movement of the focusing servo motor, the displacement of the surface from the probe can be measured, [9].

The triangulation probe technique, evaluates surface height by considering the position of the reflection from the surface on a photo-diode array. A focused Laser is directed at the surface, and the position of the

Figure 1 - Scan Length verses Gauge Range
reflected beam on the photo-diode array determines the displacement between the probe and the sample, [10].

With both Laser probe types there is a trade-off between resolution and gauge range. For example, probes are available with either a 10nm resolution and 1mm gauge range, or 0.1μm resolution and 10mm gauge range. This may present problems when measuring curved surfaces, either sufficient gauge range is available to measure the entire sample area, but resolution of the data is poor, or the resolution of the data is adequate, but their is insufficient gauge to capture the whole area.

A further problem has been observed when using these instruments. Both types of probe require that some light be reflected from the surface of the sample in order that the height of the surface can be evaluated. When considering curved surfaces, the angle of incidence of the light and surface increases rapidly as the probe moves from the centre of the sample. Once the angle of the surface increases above approximately 10° insufficient light is reflected, and the probe is unable to measure the surface. Again, on nominally spherical surfaces, this effect can decrease the sample area that can be measured, or can result in portions of the area being "dropped out" due to low intensity light returns from the surface.

2.2 Stylus Profilometer

Instruments, such as the Rank Taylor Hobson Form Talysurf, measure a surface by dragging a 2μm radius of curvature diamond-tipped stylus over the sample, monitoring the movement of the stylus and converting this movement into height data. Recently, the transducer used to monitor the stylus movement has been updated from an inductive pick-up to a Laser based Michelson interferometer, [11], details of which are shown in figure 4. This results in the instrument having a gauge range of 6mm to a resolution of 10nm, making it very versatile.

Profilometers are usually 2-D instruments, measuring a single slice of the sample. The addition of a y-axis table allows a sample to move at right-angles to the stylus, enabling the multiple parallel traces of data to be scanned to form a 3-D image.

The contact nature of the stylus with the sample's surface has both advantages and disadvantages. Surface contamination, for example small particles of dust, are pushed out of the way of the oncoming stylus, ensuring a true representation of the surface is measured.

The main disadvantages of the system are the times for measurement, typically 1.5 hours for a 10mm by 10mm scan, and the damage caused to the surface by the diamond tip. The contact force of the stylus and sample is only 10mgf, however, this force is applied over a very small area, resulting in plastic deformation of the surface on many material types.
2.3 Interferometry

Interferometry uses a monochromatic light source (typically a Laser) of a known wavelength, \( \lambda \), which is passed through a beam splitter causing light to be directed onto the sample's surface, and reflected back onto a reference surface. The two beams recombine and the interference pattern formed is incident on a CCD array. A computer is used to interpret this fringe patterns into height data.

Interferometry is an extremely accurate technique when used on surfaces that reflect a sufficient proportion of the incident light. As with the Laser probes, higher angles of light incidence result in insufficient reflection from the sample and subsequent drop outs in the surface plot. Its resolution is dependant on the aperture of the focusing lens, the wavelength of the light, and the area of sample viewed.

A number of problems have been observed in interferometers. Two of the problems that exist using this technique are microphonics and phase shift ambiguity, discussed by Somekh et al., [12]. A further problem was documented by Talke and Li, [13]. Large discrepancies were observed in step height measurements of carbon coated magnetic disks when measuring them using the industry accepted stylus profilometry techniques, and an interferometer. After considerable study, it was realised that refraction of Laser light through the carbon over-coat of the disk was introducing additional fringe patterns causing the 50% step height errors between the stylus data and the interferometer. It is believed that some of the differences in \( R_s \) parameters values for stylus and interferometers documented by Williams and Statham, [14], may also be attributed to this problem.

3. Numerical Techniques

The radius of curvature of the sample has been highlighted as being an important criteria for assessing tolerances on manufacturing process. The measurement instruments discussed above describe Cartesian points on the surface, requiring numerical routines to analyse the data. This data analysis can be carried out by best-fitting a spherical reference surface to the data set obtained from the instrument, usually achieved by the application of a least-squares algorithm. The non-linear nature of the equations which define circular and spherical shapes requires an iterative, non-linear least-squares technique, such as that presented by Whitehouse, [15], or the Gauss-Newtonian algorithm for a partial spherical cap proposed by Forbes, [16].

Unfortunately, iterative routines tend to be numerically unstable, especially if a poor choice of starting variables is chosen for the iteration. As a result of this, two new body-fitting routines have been developed by the authors; one statistical sphere-fitting method called the "Four-point Sphere-fit", and the second, a circle-fitting technique based on error curve analysis,
Detailed evaluation of these techniques has already taken place, with a considerable improvement being seen in stability and quality of results over the least-squares counterparts, and in the case of the Four-point sphere-fit, an approximate halving of processing time.

Once the best-fit radius of curvature has been evaluated, it is possible to subtract this sphere from the data set, leaving behind the errors of Form. Hence, the quality of the process can be evaluated. An example of a deviation from sphere can be seen in figure 4.

An alternative technique has also been devised for assessing errors of Form, known as "Contour Analysis". This technique involves analysing an arbitrary slice taken through the sample in the x,y plane and considering how circular this slice is. For ease of analysis, it was decided that this slice would be taken through the sample at a fixed height, hence it is a contour.

Any slice taken through a nominally spherical sample will always be circular, with departure from sphere causing distortion of this shape. For small departures, this distortion will be unobservable, therefore a routine was designed which analysed a single contour-line, greatly magnifying the deviation of the slice from a circle.

Before analysis of a contour can begin, it is necessary to gather the coordinates of points that lie on the contour. The digitised nature of the data meant that simply looking for data points at a specific height results in a very small number being found. Instead it is necessary to interpolate the data to find the coordinates of the point at the required height.

Several different search routines have been tried, the first moving along a trace, searching for a transition over the required height. Once a transition is found, linear-interpolation is carried out between the two points to get the x-position of the contour, the y-position being decided by the trace number. Unfortunately there are only two such transitions per trace, resulting in insufficient contour coordinates to perform accurate analysis. This technique does not provide sufficient definition of the lower and upper edges of the contour. Figure 2 shows how the density of the coordinates decreased at the top and bottom edges of the sample.

A different technique based on a diagonal search grid has been used instead. Here transitions are searched for in two directions, at right-angles to each other (See figure 3). Using a linear-interpolation (between points 1 and 4), it is possible to evaluate Δ. The coordinate of the contour \((x_i, y_i)\) is then given by \(x_i = (x + \Delta)\delta x\) and \(y_i = (y + \Delta)\delta y\), where \(x\) and \(y\) are the current grid coordinate of point 1. It is possible to obtain a similar set of equations for \((X_i, Y_i)\) when the transition occurred across points 2 and 3. Once the coordinates are gathered (typically 400 for a well defined contour) and stored as a numbered array, analysis can begin. Firstly a circle is fitted to the contour using a least-square circle algorithm having the following equations for the centres, \(x_o\), \(y_o\) and radius, \(r\).
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\[ x_o = \frac{1}{N} \sum_{n=1}^{N} x_n \]

\[ y_o = \frac{1}{N} \sum_{n=1}^{N} y_n \]

\[ r = \frac{1}{N} \sum_{t=1}^{N} \sqrt{(x_{n_t} - x_o)^2 + (y_{n_t} - y_o)^2} \]

Where \( N \) is the number of contour coordinates \((x_t, y_t)\) found.

**Figure 2** - shows the limited number of transitions per trace.

**Figure 3** - Interpolation of Contour Position
Once the radius and centres of the circle were known, it was possible to convert the \( x,y \) coordinates of the contour into a polar coordinate system, \((r_c, \Theta)\) where \( r_c \) is the deviation of the contour from the nominal radius, \( r \):

\[
r_c = \sqrt{(x_c - x_o)^2 + (y_c - y_o)^2} - r
\]

\[
\Theta = \tan^{-1} \left( \frac{y_c - y_o}{x_c - x_o} \right)
\]

The \((r_c, \Theta)\) is then displayed in the form of a polar plot, the deviation from the circle, \( r_c \), being greatly magnified for clarity. The positions of both the maximum and minimum diameter and radius deviations are shown, together with their angle from the x-axis. A user controlled cursor is also available to allow the deviation values to be examined at any point in the plot. To allow assessment of the astigmatism of the sample some additional data is evaluated. The diameter of the contour is again considered, however two diameters at 90° are calculated. The routine searches to find the maximum diameter in one direction and the minimum diameter at 90° to this, indicating the position of the principle axes of the sample. Once this maximum and minimum have been found, the ratio of the maximum to the minimum is calculated giving a feel for the out of roundness of the contour, and hence the astigmatism.

### 4. Results

Figure 4 shows an example of the results of a deviation from sphere plot on a contact lens mould measured using a Rank Taylor Hobson Form Talysurf. The sphere removed has a radius of curvature of 5.393\( \text{mm} \). Ideally this plot would be flat for a spherical surface, however, this is clearly not the case; the surface is showing deviation from sphere errors of ±1.3\( \mu \text{m} \) indicating distortion. The deviation takes the form of a ripple lying in the x-axis.

Figure 5 shows the same data set analysed using the Contour Analysis technique. The exaggerated contour has taken on an oval shape indicating that the component has distortion. The contour shown has a mean radius of 1.7485\( \text{mm} \) with the deviations from circle being of the order of ±10\( \mu \text{m} \). The oval appears to align with the principle axes of the plot, with the smaller dimensions corresponding to the GATE label on the figure (in line with the x-axis).
Figure 4 - Deviation from Sphere of a Contact Lens Mould

Figure 5 - Contour Analysis of Contact Lens Mould
5. Discussion

Considering the deviation from sphere plot (figure 4), a radius of 5.393mm was estimated for the best-fit sphere. The nominal radius of this component was 5.400mm, thus an error of -7μm was introduced into the component during the manufacturing process. This figure is within the ±10μm tolerance on radius of curvature specified earlier.

The deviations from sphere are quite large, ±1.3μm, indication that the distortion to the surface was considerable. Furthermore, the deviation can be seen to be a ripple across the whole surface showing that the deformation is not localised. The component measured was manufactured using an injection moulding process. It is therefore possible that strain relief has occurred when the part was removed from the metallic insert used for moulding. Alternative post-moulding shrinkage has occurred causing the sample to contract in one axis.

The Contour Analysis plot shows this distortion more clearly; the oval nature of the contour indicates that the sample has been squashed in line with the GATE (the point where the polypropylene was injected into the moulding cavity). The oval contour shows that the sample has astigmatism, that is the radius of curvature is different in the two principle axes of the measurement (x,y axes) with the smaller radius of curvature in line with the gate (x-axis).

6. Conclusions

A number of instruments have been identified which can measure curved samples. Each of these have limitations; some will have to trade off measuring the whole region specified against the accuracy of the measurement, whilst others are susceptible to measuring both the optical and mechanical properties of the surface. If the damage caused by profilometers can be tolerated, then stylus instrument’s superior gauge range, and comparable resolution makes them highly suitable for curved sample assessment.

Once a suitable measurement instrument has been selected, it is then necessary to chose a numerical algorithm to analyse the data from this instrument. Algorithm selection will depend on the information required from the data set. If radius of curvature tolerances are to be checked, then a sphere-fitting routine should be chosen, however is errors of Form are required, the information available from Contour Analysis can be considerably clearer and easier to interpret.
REFERENCES