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TITLE: ON THE CHARACTERIZATION OF SPHERICAL SURFACES

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Summary

The surface geometry of a spherical object is often incompletely evaluated because of limitations inherent in the techniques used to measure it. If several techniques measuring different aspects of the surface are combined, a more complete description can be obtained.

1. Introduction

For convenience in measurement, the study of the spherical surface can be conducted in three possibly overlapping categories. First, the overall or large-scale geometry of the part can be assessed. Second, the waviness, or longer wavelength component of surface texture, and the roughness, or shorter wavelength component, can be measured. Finally, the surface can be searched for isolated anomalies, which can then be measured and cataloged.

The overall shape of the surface can be determined by means of a number of precisely oriented roundness measurements. High accuracy diameter measurements made at known locations with respect to this measured contour provide dimensional data from which the spatial coordinates of any location on the surface can be computed.

Surface texture can be assessed by sampling representative portions of the surface. Waviness data can be obtained by making one or more roundness measurements, contacting the part with a large radius stylus to avoid damage. Roughness data can be obtained

by tracing a short section of the surface with a small radius stylus, using a very light gage force.

Surface anomalies can be detected by a full visual inspection of the surface as it rotates past the field of view of a microscope. Once located, an anomaly can be photographed to determine its lateral extent, and depth can be measured by use of a high power interference microscope. If lateral extent or depth is such as to prevent the use of light interference, the area of interest can be located beneath a stylus type profiling instrument and a profile tracing made.

2. Notation

C	A constant equal to $[(1 - \nu_1^2)/E_1] + [(1 - \nu_2^2)/E_2]$
d	Wavelength of a sine wave
D	Diameter of a sphere
E_1, E_2	Young's modulus for a flat surface and a sphere, respectively
$f(x)$	Function of the variable x

f', f''	First and second derivatives of $f(x)$, respectively
h	Amplitude of a sine wave
	Load applied to a contacting gage tip
r	Radius of a sphere
x	Lateral position
ν_1, ν_2	Poisson's ratio for a flat surface and a sphere, respectively
ρ	Radius of curvature of a function $f(x)$
$\rho_{\min}$	Minimum radius of curvature of a function $f(x)$
$\tau_{\max}$	Maximum shear stress occurring in a flat plate contacted by a sphere

3. Large-Scale Geometry

In order to completely specify the shape of a nominally spherical object, it would be necessary to obtain an infinite number of spatial coordinates of the surface. Since this is not possible in practice, it is necessary to limit consideration to that shape which can be defined by a finite number of data points, particularly if any

mathematical treatment of the data is to be attempted. This abbreviated description of the surface, which omits surface characteristics of small lateral extent, constitutes its large-scale geometry.

3.1. Three Dimensional Contour

Several means are available for obtaining the spatial coordinates of a three dimensional object. Fortunately, the spherical surface can be considered to consist of an infinite number of two dimensional circles, the measurement of which has been studied and refined to a high degree of accuracy. Two dimensional roundness gages can be obtained with radial errors on the order of 25 to 50 nm, and digitization to obtain discrete data points is straightforward.

If a number of roundness measurements are made in a known orientation with respect to one another, three dimensional data can be obtained. One easily analyzed set of orientations is that in which the plane of each roundness measurement coincides with every other such plane along a single diameter of the sphere (Fig. 1).

A device (Ref. 1) for producing the required set of orientations of the sphere on the work platform of a rotating gagehead type roundness gage is shown schematically in Fig. 2. Roundness measurements are made while the sphere is held stationary in the vertical-axis vacuum chuck. To change the plane of measurement, the sphere is transferred to the horizontal-axis chuck and rotated by means of the rotary table attached to that chuck (the common axis of all roundness measurements is defined by this rotary table). The angle through which the sphere is rotated between roundness measurements is chosen based on the maximum acceptable distance between data points at the equator of the sphere.

3.2. Dimensional Measurements

Upon completion of the desired set of roundness measurements, each intersecting the others at one common diameter, the shape of the sphere can be described in terms of radial deviation from a perfect sphere of this diameter. Theoretically, the spatial coordinates of all measured points can be obtained by measuring this diameter. In practice, it may be desirable to measure more than one diameter as a check on accuracy.

To complement the high accuracy available in the roundness measurements, it would be desirable to make this diameter measurement to an accuracy on the order of 50 nm. With care, a single axis measurement can be made to this accuracy. One method for doing so is that used in calibration of secondary length standards; namely, direct comparison with a standard of known dimensions in a controlled environment.

A more versatile method involves the use of a laser interferometer aligned so its measurement beam lies parallel to the vertical axis of a coordinate measuring machine, as shown schematically in Fig. 3. If the centerline of the beam is made to pass through the contacting gage head, errors caused by angular motion of the machine's vertical axis can, to first order, be eliminated.

The diameter can then be measured by placing the sphere on a flat table beneath the gage head and traversing the measuring machine table horizontally to locate the high point of the sphere. The sphere is then removed and the distance to the plate is measured by moving the vertical axis downward. After correcting for contact deformation and temperature effects, the diameter of the sphere can be determined.

3.3 Data Analysis

Given a set of points representing radial deviation from a perfect sphere of known diameter, the spatial coordinates of all sampled points can be determined. Depending upon the intended use of the sphere, various parameters can be computed, such as the spherical minimum radial separation, least squares sphere, maximum inscribed sphere, and minimum circumscribed sphere (Ref. 2).

In other cases, a map, such as a Mercator projection or suppressed radius view, may be more appropriate; for example, when certain types of large-scale irregularities are to be detected (Ref. 3). Finally, it may be of interest simply to store the data for later use. For example, the initial shape of a part might be stored and later compared to its shape after use.

4. Surface Texture

The assessment of the large-scale geometry of the sphere can be extended somewhat arbitrarily to include shorter wavelength components by increasing the number of roundness measurements and the number of samples taken

per measurement. Eventually, this process would be limited by the data handling capability of the associated computing system--and since decreasing the spacing between data points by a given factor requires an increase by its square in the number of data points taken, this limit would be reached relatively quickly.

Long before this point, however, the number of roundness measurements required would become cumbersome. In addition, some of the techniques used for analysis of large-scale geometry, such as mapping, are less suitable for analysis of microirregularities. It is more reasonable to measure shorter wavelength surface components by evaluating a certain portion of the surface in depth and assuming it to be representative of the whole. This assumption can be tested by comparing two or more samples.

Mechanical profiling instruments are well suited for measuring surface texture because they offer an easily digitized output signal and the mechanics of their interaction with the surface are well understood. Since a two dimensional trace across a three dimensional surface is not representative unless the surface is isotropic, it may be necessary to take measurements in several directions to fully characterize the surface.

4.1 Waviness

Correct evaluation of the longer wavelength components in a surface requires that the assessed length be at least as long as the wavelength of interest. Since in some cases it may be desirable to evaluate surface components with wavelengths as long as the circumference of the sphere, a complete roundness measurement is required as input data.

Data can be collected during one or more of the roundness measurements associated with the evaluation of large-scale geometry; however, an increased sampling rate is required to more accurately profile the surface. For accurate Fourier analysis, the number of sample points must be such that the distance between consecutive points is no more than half the shortest wavelength component present in the signal (the Nyquist sampling criterion). More points, perhaps ten times this number, are required to represent the waveform well on a plot.

In any contact type measurement, the possibility of damage caused by high local stresses in the zone of contact must be considered. Typical roundness gages, which contact the part in a horizontal direction with a

gage force in the range of 0.001 newton or greater, can be used with little danger of damage if a large radius (for example, 0.5 millimeter) stylus is used. However, small radius styli, such as might be desirable for profiling fine detail, would almost certainly cause damage even to relatively hard materials at such loadings (Appendix 1). For this reason, roundness measurements must usually be made with a large radius contacting tip.

The wavelength d of the shortest sinusoidal component of amplitude h that can be profiled accurately with a stylus of radius r can be estimated (Ref. 4, Appendix 2) as

$$d \leq 2\pi \sqrt{hr} \quad .$$

For example, in the case of a 0.5 millimeter radius stylus profiling a surface of amplitude 0.1 micrometer, the limiting wavelength is about 45 micrometers; for an amplitude of 1 micrometer, it is 200 micrometers. Because surface components with wavelengths shorter than the limiting value will be distorted, it is advisable to filter the output of the gage to remove such components before attempting to digitize or further analyze the signal.

4.2 Roughness

Surface components with wavelengths too short to be accurately profiled with the large stylus of a roundness gage can instead be measured, over a much shorter range, with a surface finish profiling instrument. Such instruments are available with extremely light stylus gage forces (0.00002 newton or less). At such gage forces, damage to even the most delicate materials can be avoided, using stylus radii as small as one micrometer or less (Ref. 5).

These instruments traverse the stylus linearly across the part. When measuring small radius spheres at high vertical magnifications, the length of traverse that can be recorded on a strip chart is often very short, because of the limited vertical range of the chart paper. If the output of the instrument is digitized, however, its usable vertical range can be increased without significant sacrifice of vertical resolution, up to a limiting value determined by the resolution and accuracy of the digitizing device and the system noise level. This technique allows an increased length of surface to be sampled.

In order that the information obtained during the roughness measurement can complement that obtained during the waviness measurement, the length of surface sampled for roughness should be long enough to allow analysis of surface components with wavelengths at least as long as the shortest component assessed by the waviness measurement. For the case of a surface of 0.1 micrometer amplitude profiled with a 0.5 millimeter radius stylus during the waviness measurement, a 45 micrometer minimum trace length would be required in the roughness measurement, though a longer trace (perhaps five times this value) is often easier to interpret. In general, trace lengths on this order are easily obtained.

4.3 Data Analysis

In many cases, a profile of the surface microstructure is all that is needed; such a profile often allows differentiating satisfactory parts from unsatisfactory ones or choosing the best of several. The digitized profiles obtained during the roughness and waviness measurement offer the additional advantage of being easily stored, allowing retrieval for future calculations or comparisons.

If desired, parameters such as the average or root-mean-square roughness, average slope, and other measures suited to the intended use of the surface can be computed. More elaborate measures reported in terms of a function rather than a single number, such as the Fourier spectrum, height distribution, slope distribution, or autocorrelation function, can also be computed without great difficulty, provided the accuracy and spacing of the digitized points are taken into consideration.

5. Surface Anomalies

The assessment of surface microstructure based on one or more sets of waviness and roughness data can be assumed to apply to the rest of the surface, or at least (in the case of nonisotropic surfaces) to certain directions on it, with the possible exception of small areas where non-typical defects such as pits or inclusions are present. Because such anomalous areas cannot be described in terms of typical properties, they must be individually detected and measured.

5.1 Detection

Anomalies can be detected, in most cases, by visual inspection with a microscope. If the surface of the sphere is rotated through the field of view of the microscope, the type, frequency, and location of these anomalies can be cataloged.

Such rotations can be performed by use of a device like that shown schematically in Fig. 4. The axis of rotation of the rotary table and that of the spindle are aligned so as to be orthogonal and to coincide at the center of the sphere, which is held in a vacuum chuck. By rotating about these two axes, motion in a spherical geometry is generated. The surface of the sphere can then be examined in a series of latitude sweeps, as shown in Fig. 5, with each sweep corresponding to an indexing of the rotary table and a full 360 degree rotation of the spindle.

Because half of the sphere is obscured by the vacuum chuck, it is necessary, in order to observe this portion, to remove the sphere from the chuck, rotate it 180 degrees, and replace it. This can be done by temporarily replacing the microscope shown in Fig. 4 with a vacuum

chuck attached to a vertical axis rotary table. The spindle axis is oriented so as to lie horizontally, and the sphere is transferred to the vertical axis assembly, rotated, and returned to the spindle chuck.

The microscope shown in Fig. 4 is of an inverted design, in which the objective lens faces upward. Though not essential, this design allows the geometry generator to be built upward from table level; it also allows the microscope to be replaced when necessary with part manipulators such as the rotation device.

5.2 Measurement

The lateral extent and shape of an anomaly can be recorded by photographing the image produced by the microscope. For a large class of anomalies, extent in the direction normal to the surface can be measured by light interference. A dual beam, rather than multiple beam, microscope design is preferable for this purpose, as contact with the sphere is not required to produce interference.

When the extent of an anomaly in the normal direction or the abruptness of change in extent prevents the use of

light interference, the sphere can be removed and located beneath a stylus type profiling instrument, such as that used for roughness measurement, and a profile tracing made. This operation must be performed carefully so the orientation of the sphere is retained. One method for doing so is to transfer the sphere, with the anomaly facing downward, to a stationary chuck, then rotate the sphere 180 degrees about a horizontal axis in two 90 degree steps using the geometry generator.

6. Conclusion

These measurement methods produce a detailed quantitative characterization of the spherical surface. Data is obtained relating to the large-scale geometry, microstructure, and isolated imperfections of the surface. This data, sufficient for an essentially complete description of the surface geometry, can be analyzed immediately or stored for future reference.

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Appendix 1: Stylus Damage

The likelihood of damaging a surface with a stylus can be estimated by computing the static elastic contact stresses. The maximum shear stress occurring in a flat surface in contact with a sphere can be computed (Ref. 6) as

$$\tau_{\max} = 0.306 \left[\frac{P}{D^2 C^2} \right]^{1/3}$$

where:

$\tau_{\max}$ = Maximum shear stress (megapascals)

P = Load (newtons)

D = Sphere diameter (meters)

$C = [(1 - \nu_1^2)/E_1] + [(1 - \nu_2^2)/E_2]$

ν_1, ν_2 = Poisson's ratio for surface and sphere,
respectively

E_1, E_2 = Young's modulus for surface and sphere,
respectively (gigapascals)

For the case of a 1 millimeter diameter steel ($\nu = 0.3$,
 $E = 210$ gigapascals) sphere in contact with a steel

surface under a 0.001 newton gage force, maximum shear stress is 70 megapascals; damage is unlikely. This case approximates the stresses present at the large radius tip of a typical roundness gage.

If the sphere diameter were instead 20 micrometers, which is the largest size available on typical surface profile instruments, the same 0.001 newton gage force would produce a 960 megapascal maximum shear stress. In this case, damage would be nearly certain.

Appendix 2: Profiling Accuracy

The spherical tip of a stylus instrument will contact the low points in a profiled surface rather than riding over them if the radius of curvature of the surface at these points is not less than the stylus radius. The wavelength at which distortion due to the finite radius stylus tip will become significant can be estimated by computing the wavelength of the sinusoid for which the minimum radius of curvature is equal to the stylus radius.

The radius of curvature of an arbitrary function $f(x)$ is defined as

$$\rho = \left| \frac{[1 + (f')^2]^{1.5}}{f''} \right| .$$

For a sine wave of amplitude h and wavelength d ,

$$f(x) = h \sin (2\pi x/d) .$$

If $h/d \ll 1$,

$$[1 + (f')^2]^{1.5} \approx 1 .$$

Then,

$$\rho \approx \left| \frac{d^2}{4\pi^2 h \sin(2\pi x/d)} \right| .$$

The minimum occurs when $\sin(2\pi x/d) = \pm 1$, for which

$$\rho_{\min} \approx \frac{d^2}{4\pi^2 h} .$$

Setting $\rho_{\min}$ equal to the radius r of the profiling stylus, it is seen that the stylus will contact the low points of any sinusoid for which

$$d \geq 2 \sqrt{hr} .$$

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