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MASTER

**A SPHERICAL INTERFEROMETER WITH
WHITE-LIGHT COMPENSATION**

R. R. Baldwin

**UNION CARBIDE CORPORATION
NUCLEAR DIVISION
OAK RIDGE Y-12 PLANT**

operated for the **ATOMIC ENERGY COMMISSION** *under* **U. S. GOVERNMENT Contract W-7405 eng 26**

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ABSTRACT

A modified form of a white-light-compensated Twyman-Green interferometer has been recently developed which can determine both the size and sphericity of concave spherical surfaces. The interferometer has an included field of view in excess of 110 degrees and will accommodate any specularly reflective concave spherical surface two inches or less in radius. Expected accuracy of the interferometer is ± 5 microinches for both size and sphericity, and repeatability should approach ± 1 microinch.

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SUMMARY

A modified form of a Twyman-Green interferometer has been recently developed for the evaluation of concave spherical segments which will be used for numerically controlled machine-tool certification. The interferometer, which can determine both size and sphericity, has an included field of view in excess of 110 degrees and will accommodate any specularly reflective spherical segment two inches or less in radius. Preliminary measurements of concave spherical surfaces cut on the Du Pont research machine indicate an expected interferometer accuracy of ± 5 microinches for both size and sphericity. Repeatability of the interferometer should approach ± 1 microinch.

After a thorough evaluation, the interferometer will be modified to accept spherical segments of a larger radius that are suitable for numerically controlled machine tool or gage certification.

INTRODUCTION

The use of spherical surfaces is becoming increasingly attractive as a method for the routine certification of numerically controlled machine tools and gages. Master circles⁽¹⁾ are presently employed to certify two-axis coordinate systems, and the master sphere would appear to be the next logical step toward certifying three-axis systems. The sphere, or spherical segment, is easily defined (from a programming point of view), relatively easy to fabricate, and requires three mutually perpendicular axes to measure.

Unfortunately, if a spherical segment is used for gage certification, someone has to certify the spherical segment. If the well-known ten-to-one rule is to apply, the spherical segment must be accurate within 10 microinches to certify that a gage or machine tool is accurate within 100 microinches. In turn, if the segment is to be certified accurate within 10 microinches, some sort of master gage is required that has an accuracy of one microinch. Although one such instrument is presently available for sphericity determination,⁽²⁾ it does not have the capability of measuring the size of the spherical radius. There are two major drawbacks to the argument that a sphericity determination and one or more diameter measurements serve to define a spherical part: (1) a spherical segment measured in this way must be at least a hemisphere in order to obtain the diameter measurement; (2) unless the segment is truly spherical, it is difficult or nearly impossible to correlate the sphericity and diameter measurements. As an example, a three-lobed part may show a constant diameter regardless of the number of diameters measured, whereas roundness charts show a constantly varying radius. In this case it is not valid to state that the radius is equal to one half the diameter at any point, nor is it valid to state that the average radius is equal to one half the average diameter.

The use of a conventional sweep gage imposes similar uncertainties. Although the sweep gage will yield a measure of roundness and the size of the radius for each sweep, it also requires a truly spherical part before it can yield an adequate definition of the part size and shape. There is, of course, the possibility of designing a sweep gage which would make an infinite number of sweeps, effectively covering the entire surface of the spherical segment with sweeps from a common center. The fabrication of such a sweep gage with sub-micron accuracy would be extremely difficult, however, and even if such a gage were developed it would be extremely tedious to analyze the data.

As a result of such problems, the burden of responsibility for defining a master spherical segment has been shifted from the metrology laboratory to the workshop, and the only accurate spherical surface presently available is the master gage ball which is too small for use in machine tool or gage certification.

The spherical interferometer with white-light compensation will, hopefully, offer a solution to the problem of accurately defining a spherical segment. The interferometer will yield a contour map of the surface under test, showing variations from a known radius. Once the true size and contour of the spherical surface are determined, the surface may be used as a master for machine tool or gage certification even though the surface contains errors of form. In addition, the interferometer may be used to draw a contour map directly on the surface, which can then be corrected by local retouching.⁽³⁾

Although the spherical interferometer is presently limited to radii of two inches or less and will only measure concave surfaces, there is no objection in principle to the use of a concave surface for certification, and the interferometer can be easily modified to accept larger radii. The interferometer in its present embodiment will be used to evaluate concave radii cut on the Du Pont research machine.⁽⁴⁾ After a thorough evaluation, the Du Pont research machine will be used to cut a spherical reference mirror of known radius. This surface, in turn, can be compared to larger spherical segments suitable for numerically controlled machine tool and gage certification.

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PRINCIPLE OF OPERATION

BACKGROUND

The spherical interferometer was developed from the Twyman-Green interferometer with white-light compensation, as a specialized modification of the original instrument. Although Twyman developed several independent modifications of his instrument which could have been used to determine size and sphericity, he was interested primarily in testing optical components and makes no mention of a spherical interferometer.⁽³⁾ He does, however, mention the necessity of obtaining accurate spherical surfaces for testing microscope objectives, which implies such an application for the Hilger microscope interferometer.^(3,5)

Houston, Buccini, and O'Neill⁽⁶⁾ have recently obtained excellent interferograms of large-radius spherical mirrors using an unequal-path Twyman-Green interferometer, demonstrating the high accuracy inherent in such an instrument. To date, however, no effort has been made to incorporate white-light compensation into such an interferometer to determine the absolute size of the radius under test.

DESCRIPTION

The compensated spherical interferometer is essentially the combination of a compensated Twyman-Green interferometer and a microscope interferometer, as shown in Figure 1. By the insertion of matched microscope objectives (① and ② in Figure 1) the plane wavefront in each arm is converted into a diverging spherical wavefront concentric with some spherical reflecting surface, s or s' . The objective, ①, is rigidly fixed at some arbitrary distance from the beamsplitter, and adjustments are provided for centering the unknown surface, s , so that it is confocal with the objective. The objective, ②, is rigidly attached to the confocal spherical reference surface, s' , and this assembly is mounted on a micrometer-driven slide which moves in the direction of the double arrow.

By adjusting the micrometer slide, the objective-mirror assembly, ②, may be positioned such that the total path length to Surface s' is exactly equal to the total path length to Surface s . At this point white-light interference fringes are viewed through the telescope, which is focused through Objective ① onto Surface s , which is under test. If Objectives ① and ② are of good quality, and Surface s' is spherically accurate, the resulting fringe pattern will be a direct measurement of the contour of Surface s ; also, the position of the micrometer moving Objective ② will indicate the value of the radius, R , provided the instrument has been previously calibrated in terms of a known radius.

Objectives ① and ②, presently used, are of a high numerical aperture (0.85), giving an included angle, α , slightly greater than 110 degrees. The largest radius which may be measured with the present instrument is two inches. This limitation is determined by the travel of the micrometer-driven slide. Any radius less than two inches may be measured.

Provisions are included for inserting an interference filter of known wavelength immediately in front of the telescope, to produce a monochromatic fringe pattern. This provision is very helpful in determining part sphericity.

Figure 1. OPTICAL ARRANGEMENT OF A COMPENSATED SPHERICAL INTERFEROMETER.

WHITE-LIGHT COMPENSATION

Although the theory of monochromatic spherical interferometry is adequately covered in the literature,^(3,5-7) there is to date no mention of white-light compensation for such an interferometer. That it can be done was evidenced beyond any doubt by the appearance of the interference microscope, without which this type of interferometer would not have been practical.

Referring to Figure 1, it is apparent that white-light fringes could easily be obtained from such a system if front surfaced mirrors were placed at Positions A—A' and B—B'. The only requirement would be that: $Z = Z'$, $D = D'$, and $\delta = \delta'$. Z and Z' represent the total distance from the beamsplitting plane to A—A' and B—B' along the path taken by any particular and conjugate light ray; D and D' the total path in air for any particular and conjugate light ray; and δ and δ' the total path in glass for any particular and conjugate light ray. In addition, the terms " η " and " η' " represent the refractive index of glass traversed by any particular and conjugate light ray. (It is assumed that $Z = D + \delta$ and $Z' = D' + \delta'$.)

Since it is well known that in a compensated interferometer, such as shown in Figure 1, there exist Planes A—A' and B—B' normal to the direction of propagation of the light rays, it only remains to describe an optical system which will maintain the required equality of glass path and air path to the indicated surfaces, s and s'.

As shown in Figure 2, the remaining optical path to Surfaces s and s' may be expressed as:

$$p = D + f(x, y, \lambda) + R, \text{ and}$$

$$p' = D' + f(x', y', \lambda) + R'.$$

The coordinate systems x, y and x', y' are defined such that if a ray passes through Point $x = a, y = b$ in the x, y system, the conjugate ray passes through Point $x' = a, y' = b$ in the x', y' system.

Let $f(x, y, \lambda)$ = optical path function of Objective ①, and

$f(x', y', \lambda)$ = optical path function of Objective ②.

If the distance, D , is fixed, but D' is variable, and if D' is adjusted so that $D' = D + (R - R')$, then:

Figure 2. OPTICAL PATH OF MATCHED MICROSCOPE OBJECTIVES.

$$p = D + f(x, y, \lambda) + R,$$

$$p' = D + (R - R') + f(x', y', \lambda) + R', \text{ and}$$

$$p = p',$$

provided: $f(x, y, \lambda) = f(x', y', \lambda)$ for all x, y, x', y' values within the region covered by the objective, and for all λ within the visible spectrum.

This last requirement imposes some rather severe restrictions on the optical components used.

If the previously mentioned point-to-point correspondence between orthogonal coordinate systems x, y and x', y' is to be maintained for any distance, D' , then the collimated white-light source must have a high degree of spatial coherence for all visible wavelengths. In addition, if $f(x, y, \lambda) = f(x', y', \lambda)$, matched objectives of high quality must be used, and they must be corrected for infinite tube length and must be viewed on axis. It is assumed that Objectives ① and ② occupy identical regions in the coordinate systems x, y and x', y' . If these requirements are met, white-light interference fringes may be obtained from two differing radii, R and R' .

CALIBRATION

To demonstrate the principle of calibration of the instrument, assume a known radius, R_0 , to be placed confocal with fixed Objective ①. Furthermore, let A equal the path length to Objective ①, and $(M + B)$ the path length to Objective ② (where M represents the micrometer reading), then the total path length in each area would be:

$$P_1 = A + f(x, y, \lambda) + R_0, \text{ and}$$

$$P_2 = (M + B) + f(x', y', \lambda) + R'.$$

If the micrometer is adjusted so that white-light interference fringes are present, then:

$$P_1 = P_2, \text{ and}$$

$$A + f(x, y, \lambda) + R_0 = M + B + f(x', y', \lambda) + R'.$$

Since $f(x, y, \lambda) = f(x', y', \lambda)$ for matched objectives:

$$A + R_0 = M + B + R'.$$

If the micrometer is now set to read the known radius, R_0 , while maintaining white-light fringes in the field of view, then $M = R_0$ and $A = B + R'$.

If an unknown radius, R_1 , is inserted in place of R_0 and the micrometer reading, M , adjusted until white-light fringes are again observed, then:

$$A + f(x, y, \lambda) + R_1 = M + B + f(x', y', \lambda) + R'.$$

However:

$$f(x, y, \lambda) = f(x', y', \lambda), \text{ and}$$

$$A = B + R';$$

so, the equation reduces to:

$$R_1 = M.$$

It is therefore possible, with a properly aligned interferometer, to measure any radius within the range of the micrometer travel, provided the micrometer has been calibrated in terms of one accurately known radius.

INTERNAL ALIGNMENT

It should be noted that, like the Twyman-Green interferometer, the spherical interferometer compares two wavefronts⁽³⁾ which may contain distortion due to errors in either or both objectives as well as lack of sphericity of Surfaces s and s' . Although interference microscope objectives are highly corrected to be free from axial errors, this condition can only be accomplished at the expense of increased off-axis error. It is therefore essential that both objectives be viewed on axis if the interferometer is to yield valid results.

Although a detailed description of the adjustments required to ensure proper objective alignment is beyond the scope of this report, several tests are included in Appendix A which will ensure that proper alignment has been achieved. Appendix B outlines the operating instructions for the spherical interferometer.

RESULTS

A prototype interferometer is presently being used to evaluate concave spherical surfaces turned on the Du Pont research machine⁽⁴⁾ to determine the suitability of such a surface as a reference mirror for the interferometer. Since the prototype interferometer is, at present, without a reference mirror of known radius, it is not possible to make accurate radius measurements with it. Sphericity comparisons have been made, however, and several excellent white-light interference patterns have been obtained from differing radii.

Figure 3 shows a comparison of two spherical surfaces differing in radius by 1 1/4 inches. The smaller-radius surface was lapped and polished, whereas the larger surface was turned on the Du Pont machine. Independent roundness measurements showed the lapped surface out of round around the circumference of the field of view by about 30 microinches. Similar measurements showed the turned surface to be round within 10 microinches or better. The photograph indicates a difference of roundness of about 25 microinches, which is in good agreement with the roundness measurements and indicates that the errors shown on the photograph are primarily due to the lapped part. Visual observation of the fringe pattern indicates that the lapped part is astigmatic in form. The interferometer is set to one of the principal radii. Those areas of the part having the set radius appear as the H-shaped white fringe centered on the crosshairs. The somewhat mottled appearance of the fringe pattern is due to an "orange peel" effect on the surface of the lapped part which had been cloth polished. In addition, a few concentric circles are just barely visible which are due to tool marks on the turned part. The pattern indicates, however, that the overall surface regularity of the turned part is much better than that of the lapped part.

Previous tests comparing only lapped surfaces showed gross errors of form, and the use of lapped surfaces will be discontinued. Twyman, who investigated the use of lapped surfaces

Figure 3. WHITE-LIGHT INTERFERENCE PATTERN.

for the Hilger microscope interferometer, encountered a similar problem:(3) "The polishing of a concave mirror.....with sufficient precision not to introduce objectionable aberrations of its own becomes very difficult in the case of objectives of high numerical aperture,.....".

Fortunately, the Du Pont machine appears capable of generating a concave hemisphere with total deviation from sphericity less than 10 microinches. By testing Du Pont parts one against the other, it should be possible to obtain the best of a series of parts for use as a reference mirror.

Once a suitable reference mirror has been found, the Du Pont machine will again be used to produce a series of calibration standards of known radius.(4) These standards will be used to determine the accuracy of the spherical interferometer, which will eventually be modified to accept spherical segments large enough to be used in machine tool and gage certification.

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APPENDIX A

TESTS FOR PROPER INTERNAL ALIGNMENT

Testing for Parallelism of the Viewing Axis and Collimated Light Axis

If the objectives are removed and cube corners substituted, as shown in Figure A-1, the two-point images of the source should be coincident in the center of the field of view, as seen through the telescope.

Figure A-1. TESTING ARRANGEMENT FOR DETERMINING PARALLELISM OF THE PRINCIPAL AXES.

Testing for Proper Angular Alignment of Objectives ① and ②

Angular alignment of Objectives ① and ② (Figure A-2) may be checked by removing the objectives and placing flat mirrors against surfaces A-A' and B-B' upon which the objectives seat. The two point images of the source should coincide in the center of the field of view.

Figure A-2. TESTING ARRANGEMENT FOR THE ANGULAR ALIGNMENT OF THE OBJECTIVES.

Testing for Lateral Alignment of Objectives ① and ②

Lateral alignment of the objectives may be checked by inserting Flat Mirrors ① and ② (Figure A-3) at the focus of each objective as shown. Each objective then acts as a "cats eye" reflector and, with the telescope focused at infinity, two-point images of the source should coincide in the center of the field of view. If the telescope is now focused on the back lens of both objectives, the two should appear coincident if they are in proper lateral alignment.

Figure A-3. TESTING ARRANGEMENT FOR THE LATERAL ALIGNMENT OF THE OBJECTIVES.

Testing for Proper Positioning of Reference Surface s'

By inserting a flat mirror, m , at the focus of Objective ① (Figure A-4), as explained in the preceding section, Objective ② may be tested to determine if it is confocal with Surface s' . If it is confocal, the two-point images of the light source will be coincident in the center of the field of view as seen through the telescope.

Figure A-4. TESTING ARRANGEMENT TO TEST THE PROPER POSITIONING OF REFERENCE SURFACE s' .

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APPENDIX B

OPERATING INSTRUCTIONS FOR THE SPHERICAL INTERFEROMETER

Initial Adjustment

Set the micrometer drum to the expected radius of the spherical surface under test. To position the surface, place it face down on the adjustable table with its center of curvature slightly above the microscope objective. Focus the telescope on the surface of the reference mirror, which will appear as a sharply defined disc when in focus. If the surface under test is now moved by means of the x-y slide on the table, a small point of light should be observed moving within the disc. Adjust the surface using the x-y slide until the point of light is centered within the disc, and begin lowering the adjustable table (being careful to maintain the point in the center of the disc). Continue to lower the table until the point spreads out into a sharply defined disc similar to that observed from the reference mirror. Refocus the telescope until the disc of reflected light from the reference mirror reduces to a sharply defined point. Using the fine adjustment to raise and lower the adjustable table, position the surface under test so that its disc of reflected light is also reduced to a point. Readjust the x-y table until both points are coincident, and refocus the telescope onto the surface under test. Insert the interference filter immediately in front of the telescope, and adjust the micrometer drum until high-contrast interference fringes appear in the field of view. Remove the interference filter and adjust the micrometer drum slightly until white-light interference fringes appear.

Centering on an Aspherical Surface —Average Radius

It is sometimes difficult to locate the average center of curvature of a nonspherical surface. This fact is especially true if different great circles of the surface have different radii. In this case it is necessary to adjust the surface in such a manner that a bulls-eye fringe pattern results. The surface will be centered correctly if the following criterion is met: The center of the bulls-eye must be in the center of the field of view. On a nonspherical surface this may be evidenced by a fringe pattern which is symmetrical with respect to the center of the field of view, although not necessarily circular.

The bulls-eye must be "opened up" as far as possible. Although this requirement seems straightforward (and is for spherical surfaces), it is the most difficult adjustment to make for a nonspherical surface since the pattern no longer resembles a bulls-eye. The objective, then, is to adjust the surface so that a minimum number of fringes appears in the field of view. The fringes should be more or less centered symmetrically about the center of the field so that if the fringes are counted in a direction radially from the center, there will be about the same number of fringes along any two opposite directions.

To determine the best great-circle radius, the surface is adjusted until a system of parallel, straight-line interference fringes results. By adjusting the surface laterally, the direction and spacing of the fringes may be varied at will. After several trials it will be apparent that one direction and spacing yields a better pattern (straighter and more widely spaced) than any other. This arrangement is the "best great-circle" pattern, and may be used to determine the best great-circle radius.

It should be noted, however, that this technique should not be used to determine sphericity.

Determining the Size of the Radius

Test for Proper Internal Alignment — The radius of an unknown spherical surface may be measured by adjusting the micrometer drum until a white-light interference pattern is observed in the field of view. If all optical components are aligned properly within the instrument, a very intense white-light interference pattern will be observed. To check for proper internal alignment, the moveable mirror should be adjusted slightly to shift the zero-order fringe throughout the field of view. If the color of the (white) zero-order fringe changes during this adjustment, or if a different fringe becomes the zero-order fringe, misalignment is present. In the event of severe misalignment, the white-light interference pattern will be grossly distorted, and no definite zero-order fringe will be observed. It should be noted that the interferometer must be properly aligned if radius measurements are to be attempted. For detailed alignment tests refer to Appendix A.

Adjusting for Equal Path Length — Once it has been determined that no internal misalignment exists, the moveable mirror is adjusted by means of the micrometer until the white, zero-order fringe crosses the center of the field of view. The spherical surface to be measured is then adjusted to spread out the zero-order fringe until it covers as much of the field of view as possible. The radius of the spherical surface in inches is then read directly from the micrometer drum.

Adequately Defining the Surface Under Test — After proper adjustment it may be noted that the zero-order fringe does not cover the entire field of view. If no adjustment can accomplish this due to irregularities in the fringe pattern, this problem is due to non-sphericity of the surface under test.

In order to adequately define the surface, it must be marked for identification and a photograph of its white-light interference pattern taken through the interferometer. Identifying marks should be adequate to properly orient the surface and should be visible on the photograph. Such a photograph, together with the radius measurement, will define the surface.

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