Interferometric Measurement of Sphere Diameter

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An interferometer-based system for measuring the diameter of spheres is being developed at University of North Carolina at Charlotte. Our goal is to measure spheres up to 3 inches in diameter with an uncertainty of 10 nm or less. To reduce sensitivity of the instrument to parameters like temperature, pressure and humidity, measurements will be performed in a controlled environment. To determine the size of the sphere under test, a number of corrections need to be applied to remove effects of deformation introduced by the measurement process itself. Based on the design presented in this paper, an error budget in accordance to 'Guide to the expression of Uncertainity in Measurement' has been developed.

Introduction

Measuring the absolute diameter of precision spheres remains a challenging task for metrologists. Previously, comparative techniques were considered sufficient for accurate quality control of the dimensional measurements. As the need for more accurate measurements evolves, almost all measurement systems utilize interferometry for calibration at the highest precisions. Gage blocks, representing a relatively simple geometry, are being calibrated all over the world using interferometry and today uncertainties in these measurements have been reduced to a few nanometers. Even though a sphere may be considered a relatively basic geometry, an instrument which can determine its diameter with the uncertainties comparable to gage blocks has yet to be demonstrated. In this current development, the same gage block measurement technique is adapted for measuring the diameter of spheres.

Precision spheres have lot of metrological applications including the ball bearing industry, Gravity Probe-B experiment [1], spindle error analyzers, Co-ordinate Measuring Machine references spheres and probe tips , Avogadro mass standard project [2] to name but a few. The motivation for development of this instrument is to make an optical measurement system with a lowest possible uncertainty. This work is based on an instrument at NIST which measures spheres.

State of the Art

Measuring spheres has its own importance and most national labs have their own dedicated sphere measurement facility. Measurement techniques vary from one laboratory to another. While most involve combinations of diameter and roundness measurements, it is clear that uncertainty in those measurements vary considerably.

Dimensional metrology facility at NIST (National Institute of Standards and Technology) provides calibration of typically high end precision spheres using roundness, surface form measurements and diameter measurements at multiple orientations. The Strang Monochromatic Fringe Viewer [3] at NIST is used to measure spheres up to one inch in diameter. It uses a cadmium light source to illuminate the field of view. The concept behind the apparatus is forming a Fizeau Interferometer between two optical flats with the test sphere is placed between them. The method consists of measuring the distance between the two optical flats when the sphere is contacted with a defined force. The fringe fraction is calculated in a similar way as it is calculated for gage blocks [4], [5].NIST uses the same apparatus mentioned in [3] for measuring spheres also (as of writing this has not been published). In all cases, measurements are performed in temperature controlled environments. The final value reported will be the undeformed diameter and an uncertainty budget associated with the measurement. The objective of our development is to expand the range of this apparatus for measuring spheres of up to 75 mm and also add software capability for computing fringe fraction at the center of the sphere.

Key Components of Metrology System

Key components of the measuring instrument are shown in figure 1 below. In this, the sphere will be contacted between two, parallel optical flats. Fizeau interferometry is the used for obtaining the interference fringes between the two flats and between the individual flats and the sphere in a region surrounding the contact point. Precise adjustments are incorporated for aligning the two flats to obtain fringes.

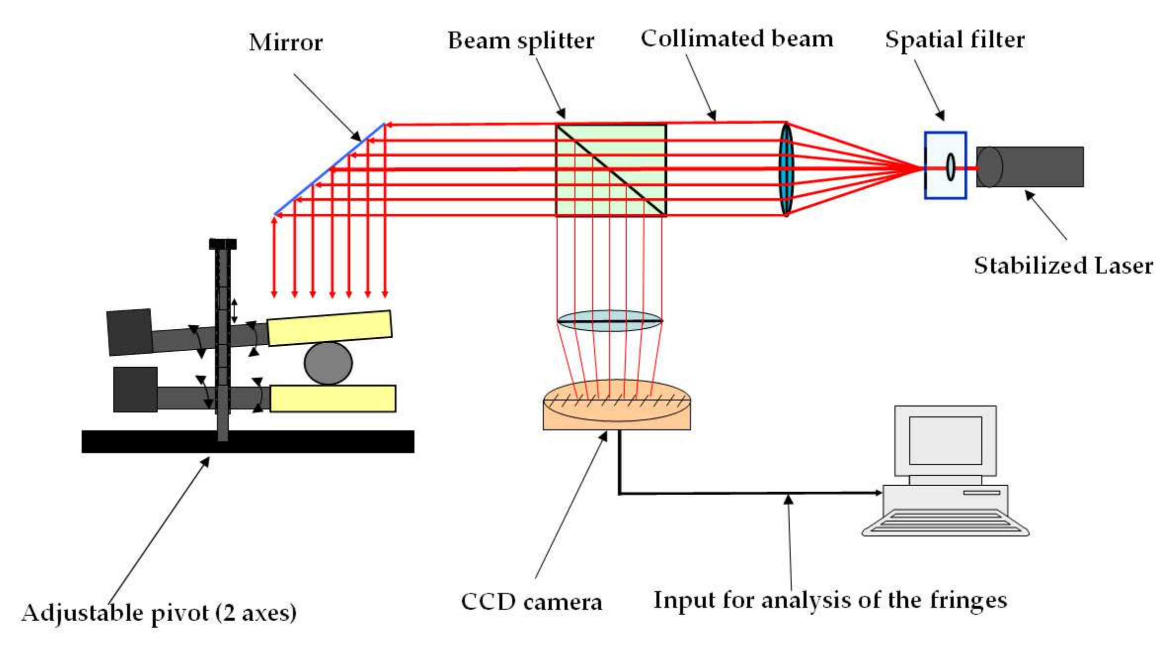
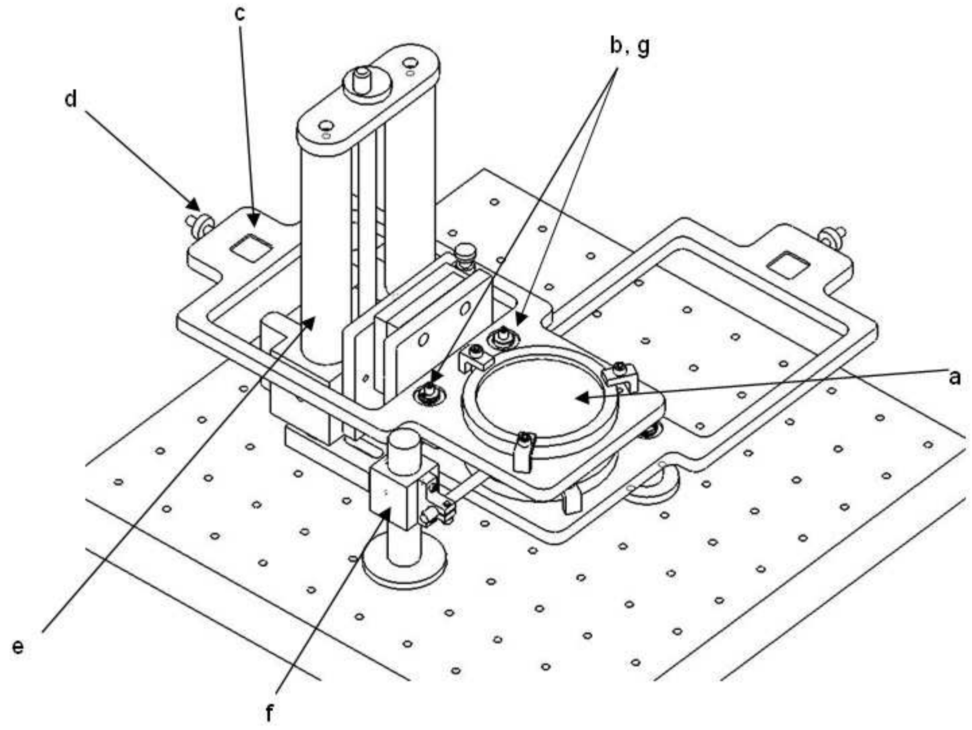


Fig 1: Setup of the Interferometer

The optical flats are housed in a 'see-saw' mechanism with a kinematic pivot and the contact force is carefully controlled using dead weights applied on the opposite side. To accommodate different diameters of sphere, the complete mechanism can be raised and lowered. Angular alignment for adjustment of the fringe spacing is achieved using fine adjustment screws, see fig. 2. In practice, the lower see-saw mechanism is below the top see-saw with parallel pivot axes. To clarify understanding of the operating principle the lower see-saw has been rotated and shows the pivot axes to be perpendicular to each other in fig 2.



a) optical Flat, b) fine adjusting screws for angular spacing, c) provision for dead weights, d) counter weight, e) coarse motion stage, f) sphere mount, g) kinematic pivot

Fig 2: Solid model of the pivot mechanism

Desired forces are applied by adding or removing the weights while the test sphere is suspended on a fixed mount (f is fig 2). Both the top and the bottom optical flats are brought into contact with the sphere by adjusting the position of the dead weights relative to the ‘see-saw’ pivot.

By definition a perfect sphere has all the points on the surface at equal distance from the center. In practice, sphericity, surface finish/form, and out-of roundness constitutes some of the geometry related factors that deviates the sphere from its ideal condition. Three precision spheres of grade around 2.5 micro inches are being used for performing the experiments

Sphere is glued using a 5 minute epoxy to the end of a non magnetic steel shaft and held rigidly in this fixture (f in fig. 2). In these initial studies, to assess instrument repeatability, it is necessary to minimize diameter variations due to roundness errors by ensuring that measurements are taken at defined points across the spheres. To do this, the steel shaft can be rotated about its axis and has markings about its circumference that can be used to define the relative orientation at which different diameters are measured.

A stabilized He-Ne laser used to illuminate the field of view with the subsequent interference fringes being imaged using a CCD camera. Standard algorithms will be used to unwrap phase wherefrom fringe fraction is calculated. Algorithms will also be developed for providing a measure of the out of roundness of spheres and the separable errors in the optical flats. Multiple readings are taken in different orientations of the spheres to average out the errors due to these factors.

Round-robin tests are also being performed at NIST on the spheres used in this development are in progress and measurements obtained from this instrument will be compared.

Sources Contributing to Uncertainty

There are many factors that contribute to the uncertainty in the measurement. To get the undeformed size of the ball, a number of corrections need to be applied. Uncertainty is calculated in accordance to ‘Guide to the expression of Uncertainity in Measurement’.

For high precision instruments and machines temperature is the major contributor for uncertainty. Temperature change especially in interferometry effects the measurements in two ways. Change in ambient temperature will change the refractive index of air and thereby changes the wavelength of laser. There will be change in the dimension of the part also. All these corrections can be added to the final value to get the undeformed diameter. However there is an uncertainty involved in temperature measurement itself which contributes to the final value. Assuming the Coefficient of thermal expansion of the material is known to 10% of its value. The standard uncertainty due to temperature is calculated to be $.08 \times 10^{-6}$ L (L is the diameter of sphere under test in meters).

Since the two optical flats are in contact with the sphere at two points. Hence there is Hertzian deformation [6] and has to be added to the final value. These equations hold well for smooth surfaces and the calculated standard uncertainty is 0.3×10^{-9} m.

Wavelength corrections for temperature, pressure and humidity also need to be added. Edlen’s equation is still widely being used for estimating these corrections. The difference between experimental measurements when compared to the Edlen’s equation is insignificant [7], [8]. Standard uncertainty in the simplified Edlen’s equation is 1.5×10^{-7}.

Optical flats used in this instrument are flat to 1/20 of the wavelength of laser being used. The optics used in the instrument also contains errors and have to be calibrated .The most common way to do it is by three-flat test. While it is known the flatness error can be substantially reduced [9], [10], an evaluation of the resultant uncertainty has not, as yet, been evaluated.

Acknowledgements

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