MEASUREMENT OF THE ABSOLUTE DIAMETER OF CYLINDRICAL GAGES BY GRAZING INCIDENCE INTERFEROMETRY

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1.0 Introduction

Grazing incidence interferometry has been applied successfully to the measurement of the form of cylindrical parts [1]. An extension of this technique for the measurement of absolute diameter by comparison with a calibrated artifact of similar diameter (typically within 4-10 μm) has been described previously [2]. This limitation is directly attributable to the 2π phase ambiguity inherent in this kind of measurement, and necessitates the use of a series of calibrated artifacts to cover a range of diameters. This paper describes a further extension that permits absolute diameter measurements over an extended dynamic range (over 25 mm with sub-micron resolution) using only one calibration master. Sources of measurement uncertainty are identified and discussed briefly. Results of absolute diameter measurement are compared with traditional two-point contact measurements and are observed to agree to better than ±0.1μm.

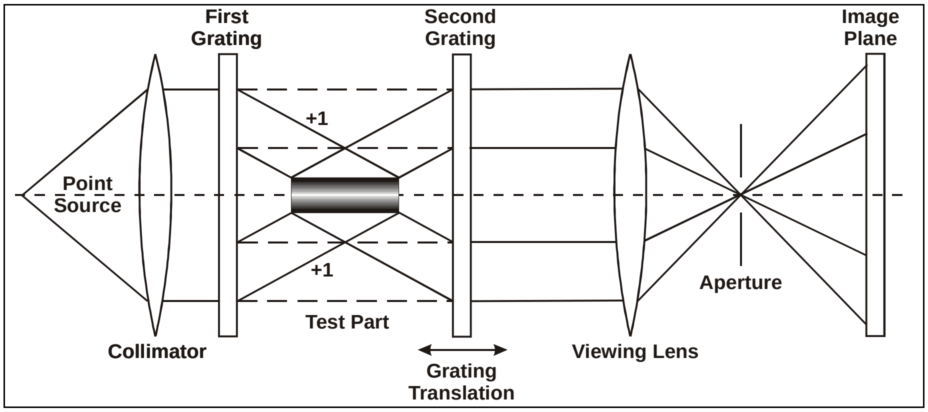

Figure 1: Optical layout of grazing incidence cylindrical interferometer

2.0 Principle of operation

Interferometric inspection of cylinders uses high precision diffractive optical elements to produce wavefronts which precisely match the surface of a perfect cylinder (see Figure 1). The first diffracted orders (+1 for OD parts and –1 for ID parts) from these circular diffractive elements produce a converging cone (diverging for ID parts) of light which strikes the part at grazing incidence. The zero order beam remains undeviated and provides the reference wavefront. The beam reflected from the part provides the test wavefront and interferes with the zero order diffracted beam at the second grating. The annular fringe pattern is imaged by a lens onto a CCD camera. An aperture located between the lens and the image plane is used to block unwanted diffracted orders. Deviations of the test cylinder from a perfect cylinder show up as phase differences in the interference pattern. Conventional phase measuring interferometry (PMI) is used to obtain accurate surface height data over the entire surface of the cylinder. The second grating is moved to modulate the fringes for PMI.

The deviations from a perfect cylinder are analyzed by fitting a series of orthogonal polynomials (Legendre-Fourier polynomials [3]) to the raw data. The constant term of this fit is referred to as the constant phase term or the 'piston' term, and is typically discarded. The higher order polynomial coefficients are representative of the magnitudes of the common form errors encountered in typical industrial parts. In contrast to traditional contact roundness gages, the non-contact/interferometric nature of this technique enables rapid measurement (less than 1 minute) of the entire surface of the cylinder.

3.0 Theory of absolute diameter measurement

Measurement of the absolute diameter of a cylinder is based on the observation that the constant or average phase ('piston') term is proportional to the diameter of the part. This term is typically discarded during a form measurement as it contains no form information and is similar to radius suppression in traditional roundness measurement. The piston term is similar to the radius of a best fit cylinder fit to a cylindrical form data set. Figure 2 shows the dependence of the output of the interferometer on the diameter of the part. A change in the average diameter of the part results in a proportional change in the piston term. The constant of proportionality is known as the fringe sensitivity S and is the change in diameter corresponding to 2π radians (one fringe) of phase change. However, this variation is cyclical due to the fact that the interferometer ultimately measures the phase difference which is a periodic quantity with a period of 2π radians. This implies that two parts with diameters differing by a dimension corresponding to 2π radians of phase change, or one fringe, are indistinguishable. In other words, unless some method is available to determine the number of integral fringes between the two diameters, the diameter is known only to within the unambiguous range of one fringe. This phenomenon is referred to as phase ambiguity and is a drawback common to many forms of interferometry.

Differences in diameter may be tracked without ambiguity within 2π radians of phase change. This property may be exploited [2] to measure the diameter of a part by comparison to a calibrated master with the *a priori* restriction that the parts do not differ in diameter by more than one fringe (typically 4-10 µm).

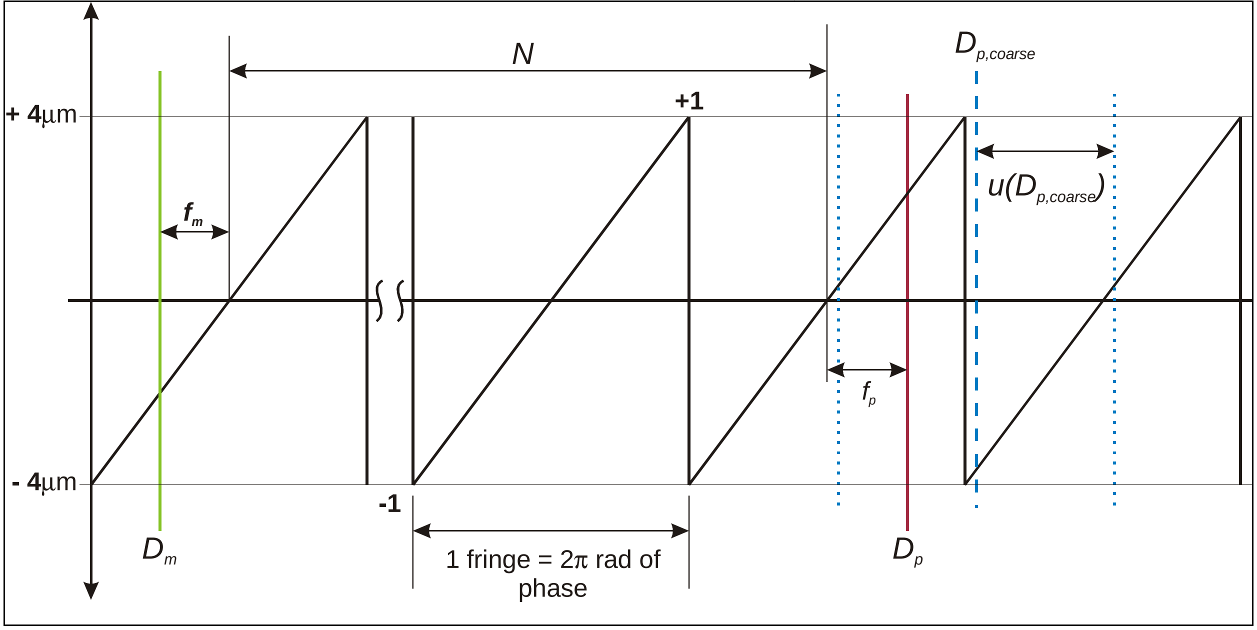

Figure 2: Principle of absolute diameter measurement

The measurement of parts that exhibit large differences in diameter (greater than one fringe) relative to the master requires resolution of the phase ambiguity. The principle of this measurement is illustrated in Figure 2. The measurement is a comparison measurement with the instrument zero being determined by the diameter of a calibrated master D_m. The number of integral fringes N, between the diameter of the master and test part may be determined from a relatively inaccurate estimate (hereafter referred to as the coarse measurement) $D_{p,coarse}$, of the diameter of the part under test, the sensitivity S, and the measured piston term for the master f_m. A refined estimate of the diameter of the test part may be obtained from

$$D_p = D_m + S(N + f_m + f_p) \tag{1}$$

where f_p is the measured piston term for the test part. In order to determine N without ambiguity, the uncertainty $u(D_{p,coarse})$ associated with the coarse measurement cannot exceed one half fringe. This is represented graphically in Figure 2 by the two dotted lines disposed in a symmetric fashion about the coarse estimate $D_{p,coarse}$. It can be shown that the sensitivity S is equal in magnitude to the pitch of the gratings or alternately, one fringe is equivalent to the grating pitch. It is significant to note that the sensitivity is independent of the wavelength of the source used to illuminate the part. The unambiguous range is then equal to the grating pitch and the maximum uncertainty of the coarse measurement is half the grating pitch. For a typical grating pitch of 8 µm, this imposes an accuracy requirement of ± 4 µm on the coarse measurement. For a typical part diameter of 25 mm, this represents a relatively trivial measurement with an instrument such as a micrometer. This requirement may be further relaxed by increasing the grating pitch at the expense of the achievable resolution. This technique is essentially similar to the Method of Excess Fractions [4].

4.0 Measurement procedure

This technique is tested by measuring five XXX Grade steel gage pins ranging in size from 5 to 25 mm in diameter. All pins are approximately 50 mm long. The separation of the gratings remains unchanged during the measurement, except for the motion required to modulate the fringes for PMI. The measurement was made at a nominal air temperature of 20°C with the temperature of the air in the vicinity of the pin being measured and recorded as each pin was measured. A maximum change in temperature of approximately 0.2°C was recorded over the entire measurement period of approximately four hours.

The average diameter of each of the pins was determined by comparison to steel gage blocks. The measurement was made on a LVDT based comparator between a flat anvil and a spherical diamond stylus. The diameter of the pin was measured along two mutually orthogonal diameters at five equispaced sections along the pin. The measured values are corrected for the effects of temperature and Hertzian deformation. The average of these corrected measurements is considered to be the average diameter of the pin.

The zero reference is set by measuring the calibrated master and recording the piston term. The master is then replaced with the test part and a measurement is performed to obtain a piston term for the test part. The pins are aligned with the optical axis of the interferometer before each measurement. The piston term reported by the machine is used in the computation of the average diameter. In this particular case, the nominal size of the gage pins is used as the coarse estimate of the diameter as the tolerance requirements on the XXX pin ensure that the accuracy requirement on the coarse measurement is met. This estimate is used to determine the integral number of fringes between the master and the test part. This information is then combined according to Equation 1 with the piston terms obtained for the master and test to provide a refined measure of the average diameter of the part.

Table 1: Sources of uncertainty in absolute diameter measurement

S. No	Source of uncertainty	S. No	Source of uncertainty
1	Value of grating pitch	7	Error due to support plate
2	Size of master	8	Phase change upon reflection
3	Thermal effects on part size	9	Computation of constant phase term
4	Frequency stability of laser source	10	Evaluation of phase
5	Change in refractive index due to environmental factors	11	Tilt and decenter of the part
6	Change in grating separation	12	Wavefront aberrations

There are a number of sources of uncertainty in the measurement which are summarized in Table 1. The sources of uncertainty impact various aspects of the measurement. The uncertainty associated with the value of the grating pitch directly affects the gain of the measurement. The uncertainty in the size of the master is an uncertainty in the zero setting or offset of the instrument. Further, differences in temperature from 20°C result in uncertainties in the diameter of the part and master. The remaining terms are uncertainties in the measured piston term. They constitute sources of uncertainty which contribute a change in the measured phase not directly attributable to the average diameter of the part. Sources 3-4 contribute to the change in measured phase by virtue of the fact that the path lengths of the test and measurement beams are slightly different and are analogous to a unbalanced displacement measuring interferometer in this regard. The frequency stability of the source only affects the measured phase by virtue of this imbalance, but does not affect the sensitivity (unlike a displacement measuring interferometer). Changes in grating separation between successive measurements either due to thermal expansion or non-repeatability of the initial position of the moving grating during PMI affect the result through the path imbalance. The uncertainty due to phase change upon reflection is a subtle effect that stems from the fact that this phase change is variable and depends of the material and surface finish of the part. This results in a contribution to the measured piston term that is not related to the average diameter. This can be significant particularly when the master and test exhibit significantly different material and surface properties. There is also an uncertainty associated with the evaluation of the measured phase by PMI. Tilt and decenter of the part relative to the optical axis of the machine also have the potential to affect the average diameter value. Further, the system utilizes a high quality collimator to collimate the beam incident upon the grating. Any aberrations in the wavefront can also cause changes in the average phase as different portions of the grating/wavefront are utilized for measuring parts of different sizes.

5.0 Results of measurement and future work

The results of measurement are shown in Figure 3. Nine experimental runs are shown. The 5 mm pin has been chosen as the calibration master. In each run, the pins are measured in sequence from the smallest to the largest. A least squares line is fit to the diameters of the pins as measured by two-point contact measurement and as reported by the grazing incidence interferometer with a nominal grating pitch value of 8µm. The slope of this line is seen to deviate from unity by approximately 40 ppm. This suggests an uncertainty in the value of the grating pitch at the sub-nanometer level which is well within the uncertainty for this quantity. The grating pitch is adjusted by this amount to achieve unit slope. Figure 3 shows deviations from this line with unit slope. The maximum residual is observed to be approximately 0.12 µm. The maximum spread of the measurement is approximately 0.04 µm which is considerably lesser than the maximum deviation. These results should be viewed in the context of the uncertainty associated with the two-point contact measurement of the pins, which is represented by the error bars in the figure. The current best estimate of this uncertainty is 0.15 µm (k=2). This suggests that the uncertainty of the measurement is dominated by the uncertainty in the average diameter of the pins. No significant drift is seen in the measurement.

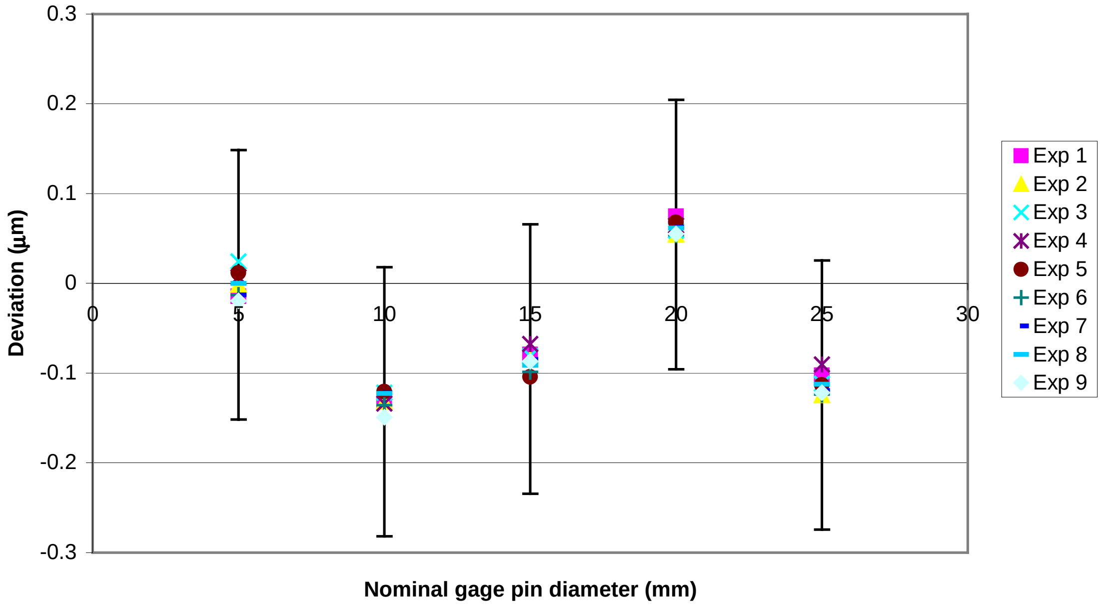

Figure 3: Results of absolute diameter measurement with 5mm pin as the calibrated master

Several additional investigations are currently underway. In order to further characterize the accuracy of this technique, better estimates of the pin diameters are required. An uncertainty statement for the measurement is currently under development. Possible systematic errors which provide opportunities for mapping are being investigated.

The measurement of absolute average diameter using a grazing incidence interferometer over large dynamic ranges has been demonstrated. The maximum observed error relative to the current best estimates of the average diameter from two-point contact measurement is 0.12 µm. Currently, the largest source of uncertainty is the size of the pins. This technique demonstrates the potential for the measurement of absolute diameter with sub-micron accuracies in conjunction with a form measurement over the entire surface of the cylinder under test.

References

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