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Evaluation of a Scanning Hartmann Device for Single Point Turning Applications*

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ABSTRACT

This paper concerns a new, machine mounted aspheric metrology device designed to measure a broad range of figures without the use of auxiliary optics. A prototype device, based on the classical Hartmann test, called a Hartmann Optical Surface Tester (HOST) was evaluated on a single point diamond turning machine. Design, initial testing, and validation data from reference spheres, and two types of aspheres will be discussed. Results of a simulation model for estimating acceptable alignment errors for the HOST on the diamond turning machine will also be presented. Peak-to-valley measurement uncertainty on the test optics was found to be better than $0.08\ \mu\text{m}$.

1. INTRODUCTION

The Optics MODIL is integrating metrology in- and on-process as part of an effort to improve quality, shorten delivery times, and lower cost of precision fabricated mirrors. In this paper, *on-process* measurements are carried out as a separate step between fabrication steps, whereas *in-process* measurements are real-time measurements carried out during the machining process and may be used to provide feedback control. Single point turning technology has been proven for broad range of aspherics used in infrared systems. Recent advancements have extended the range of the technology to systems operating at visible wavelengths and emphasize one of the major remaining problems, the lack of suitable aspheric metrology.

The precise positioning, vibration damping and thermal control necessary for high quality diamond turning are very conducive for application of metrology devices. The single point turning machine used in the Optics MODIL test bed is a prototype of the Nanoform 600 machine produced by Rank Taylor Hobson, Keene, NH.

Various metrology devices have been adapted to diamond turning machines for certifying the optical figure.^{1,2,3,4,5} In many cases, a standard interferometer or derivative is placed on the machine to measure the optics. The major drawback in this approach is the limited dynamic range of interferometry in measuring departures from spherical or null configurations. In addition, complicated setups must be used to test many of the optics that can be generated by single point turning.

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The Hartmann Optical Surface Tester (HOST) has many advantages for measurements with moderate accuracy (1/4 to 1/10 wave, $\lambda=0.6328\ \mu\text{m}$). Based on the classical Hartmann screen test⁶, it has an inherent ability to test any optic from flat surfaces to high slope general aspheres. The only requirement is that the caustic or return rays be within the capture region of the detector positioning mechanism. In addition, no auxiliary optics are needed which may compromise the measurement accuracy. Basically, the fundamental measurement is one of position measurement which has a very mature state of the art. Many interferometric and other aspheric metrology methods are data output density limited, and the state of the art is still rapidly advancing.

In the development of this integrated metrology instrument, we sought to provide a versatile certification means of moderate accuracy for the large departure aspheres that are possible with single point diamond turning technology. At present, the accuracy of new single point turning machines approaches 1/10 wave peak-to-valley (P-V) for certain optical components. If careful attention is paid to the critical parameters in the diamond turning process, 1/4 wave P-V accuracy can be routinely expected.

2. INSTRUMENT DESCRIPTION

The HOST was designed to be easily interfaced to diamond turning machines (Figure 1) and be easily automated for on-process compensation and in-process control applications. Manual location of the source and detector positioning was chosen as a proof of principle since automation was a straightforward development but too expensive for the initial phase of the demonstration. For larger optics, an auxiliary metrology frame with slides attached to the Z-axis slide will allow the HOST to be located at distances further from the surface.

As seen in Figure 2, the HOST consists of a narrow pencil laser beam which accurately pivots in two axes about a point in space. This point mimics the diverging point source of the classical Hartmann test. The pencil beam reflects off the surface of the mirror and strikes a detector in the test plane. By scanning the laser beam and simultaneously drawing the detector to a null position, data similar to that of the classical test are produced, but in real-time. Since no Hartmann screen is required, the HOST may be easily and quickly adapted to any test mirror. Sampling frequencies may be adjusted so that areas with particularly large slope errors are covered by more data points. Furthermore, the HOST detector may be placed inside the caustic (at the circle of least confusion, for example) in order to minimize the detector micrometer range of motion.

The source is positioned at the intersection of the azimuth and altitude scan axes to within 5 microns. This intersection becomes the location of the pinhole through which the pencil laser beam emerges. High precision altitude (Teledyne Gurley model 25/04S) and azimuth (Heidenhain model ROC717) digital encoders provide 5 arc second resolution for pointing of the laser beam on the optical surface. This yields a beam position accuracy, on a mirror with a 500 mm radius of curvature, of under 13 microns. In order to make accurate measurements with the Hartmann method, the two axes of rotation at which the light beam is emitted must closely intersect and be highly orthogonal.

The reflected beam positions are measured with a UDT model SC/10-D quadrant detector. The detector signal is integrated to average the effects of vibrations and random air currents. The detector is mounted on a two-axis stage with linear micrometers having resolution of one micron, and is translated until a null reading is obtained.

HOST coordinates are interfaced to the test mirror with a pair of polished tooling spheres. The position of the source and detector relative to the tooling spheres was measured to about 15 microns. These positions, along with the measured locations of the tooling spheres relative to the diamond turning spindle, enable the absolute position and orientation of the HOST to be determined.

Figure 1. HOST On-Machine Measurement

3. THEORY OF OPERATION

Parameters needed for surface error extraction are summarized in Figure 3. The source is placed at a distance σ from the test mirror vertex and a height ϵ from the test mirror optical axis z . The detector is moved to a height η relative to the axis, and has distance ω from the test mirror vertex. An exact ray trace is performed to determine the ideal value of η . Subtraction of the ideal from the measured η and division by ω gives (roughly) the surface slope error. In the data collection process, the laser beam is scanned through a series of α and β (azimuth and elevation) scan angles as determined by the user, x and y points on the test mirror are calculated from the known values of α , β , ϵ , and σ . Data may be collected along a diameter or along a circular zone of the test mirror.

In a conventional Hartmann test, the source and the detector are both located near the test mirror's center of curvature. The source and the detector are decentered by small amounts in order to avoid obscuration of the light. These decentrations introduce off-axis aberrations, such as coma, into the reflected rays. These aberrations must be taken into account in the data analysis. In conventional tests mirror asphericities are small, f /numbers are large, and the decentrations are small so that the off-axis aberrations are also small and may be modeled using third-order aberrations theory. The third order aberrations may be calculated from the known mirror parameters and decentrations, and subtracted from the measured data. However, in HOST testing the asphericities are larger, test mirror f /numbers may be faster, and asphericities may be more complicated than in conventional tests. Therefore, third-order aberration theory is no longer adequate to model the effects of source and detector decentration. Ideal reflected beam positions are thus predicted using exact ray tracing which takes into account the actual test configuration. Thus, aberrations introduced by source/detector decentrations are automatically taken into account, as are large mirror asphericities and fast f /numbers. The exact ray trace gives a reflected ray position which may be compared to the measured ray position to obtain information about the actual mirror surface.

Figure 3. Parameters used in HOST Mathematical Analysis

In the nomenclature of Figure 3, η_x and η_y are the quantities to be determined by the ray trace. η_x , the reflected ray height in the x direction at distance ω , is given by

$$\eta_x = x + (\omega - z) \tan \gamma_x \quad (1)$$

A similar equation is obtained for η_y , with all x's replaced by y's. The ray intersection point on the test mirror, x and y, is known from the data acquisition portion of the software. The mirror sag is z at point x,y, and $\gamma_{x,y}$ are the reflected ray angles in the x and y directions. These angles may be found with the following vector form of the law of reflection:

$$\vec{S}_r = \vec{S}_i - 2 (\vec{S}_i \cdot \vec{M}) \vec{M} \quad (2)$$

Where $\vec{S}_r$ and $\vec{S}_i$ are unit vectors along incident ray vectors and $\vec{M}$ is a unit vector along the local mirror normal.

The components of $\vec{S}_r$ and $\vec{S}_i$ are the direction cosines l_r, m_r, n_r , and l_i, m_i, n_i (in the x,y,z directions) of these rays. Thus, the following relations exist

$$\tan \gamma_x = l_r / n_r, \quad \tan \gamma_y = m_r / n_r. \quad (3)$$

$\vec{M}$ may be computed from the equation which describes the ideal mirror. $\vec{S}_i$ may be computed from known quantities as follows:

$$\tan \alpha_x = l_i / n_i = (x - \epsilon_x) / (z - \sigma), \quad \tan \alpha_y = m_i / n_i = (y - \epsilon_y) / (z - \sigma) \quad (4)$$

where ϵ_x and ϵ_y are the source displacements from the test mirror optical axis in the x and y directions, α_x and α_y are the x and y angles of the incident ray relative to the z-axis.

The next step in the HOST data analysis is the derivation of an equation which gives the error in the η 's as a function of s, $(ds/dz)_x$, and $(ds/dz)_y$, the errors in the mirror sag and x and y slopes. Rough estimates of the slope errors may be obtained from the following equations:

$$(ds/dz)_x = 1/2 \Delta\eta_x / \sigma \quad (5)$$

(similar for y) where the $\Delta\eta$'s are the differences between the measured and the ideal reflected ray heights. The factor of two is needed since the reflected rays are inflicted with twice the slope error of the mirror. In the HOST software, more accurate values of the surface and slope errors of the mirror are obtained via the following Taylor series:

$$\Delta\eta_x = (s \partial/\partial z + ds/dx \partial/\partial m_x + ds/dy \partial/\partial m_y) \eta_x(z, m_x, m_y) \quad (6)$$

(similar for y). Here, m_x and m_y are the x and y components of the mirror normal $\vec{M}$ (see equation 2). η_x and η_y are given by equation 1. Equation 6 reveals the fact that a ray height error in the x direction, for example, may be caused by both x and y slope errors. The strength of this cross-coupling depends on the source position relative to the point on the mirror being measured. With s initially set to zero, equation 6 may be solved for the slope errors. These initial slope values may then be used to obtain an initial estimate of the surface error s. In the case of vertical linear scans, the y slope error is multiplied by the local y data interval, then added to the surface error for the previous data point in order to give the new surface error (similarly for horizontal linear scans).

For azimuthal scans, the x and y slopes are transformed into a single θ slope in the direction of the local polar θ vector. This θ slope is then multiplied by the length of the arc between data points to give the change in the surface error. The new estimate for the surface error is then inserted into equation 6, and the process is repeated to give a better estimate of the slope errors.

Both trapezoidal and Simpson's rule (parabolic) integration⁷ of the slope data are performed. Simpson's rule provides a smoother surface representation than trapezoidal integration, but may mask small surface details. For the HOST software, the usual Simpson's rule formulation was modified to permit non-uniform data spacing and to provide surface error information at each data point rather than at every other data point. Thus, any desired data pattern (along a diameter or zone) may be used.

A polynomial fit procedure is provided to aid in the removal of alignment aberrations from the surface errors. The theory behind this procedure is that all aberrations may be represented by smooth polynomials, in particular polynomials representing piston, tilt and focus terms. Any third-order coma or spherical aberration terms are likely to be caused by misalignments, and may also be subtracted. The remaining surface errors should now give a good indication of the true mirror profile. The polynomial used in the HOST software is of the form

$$W = a + by + cy^2 + dy^3 \dots + () y^{n-1} \quad (7)$$

for linear data, or

$$W = P + C1 \cos \theta + S1 \sin \theta + C2 \cos 2\theta + S2 \sin 2\theta \\ + \dots + C(n-1) \cos (n-1)\theta + S(n-1) \sin (n-1)\theta \quad (8)$$

for zonal data. $a, b, c \dots$ and $P, C1, S1 \dots$ are the coefficients sought in the polynomial fit.

4. SIMULATION

A software program was developed for assessing the accuracy of the HOST surface error extraction algorithm and for modeling any misalignments which may occur. The test mirror used for this study has parameters similar to those of the mirror actually used for testing by the HOST. These parameters are: spherical surface, 60 mm diameter, and 254 mm radius of curvature. For a perfect test setup, the HOST software returns a peak-to-valley surface error of 0.0002 waves.

The most common misalignments include longitudinal (along z) and lateral displacements of the HOST relative to its desired location. These displacements may occur due to errors in measuring the HOST position or inadvertent shifts of the HOST from its originally measured position. Since laser beam positions are determined from the encoder angles, these misalignments displace the beam (on the mirror) from its desired position. Errors in the reflected beam position thus occur. These errors are assumed by the software to be caused by surface slope errors, and thus reappear as mirror surface errors. Longitudinal errors cause chiefly focus errors, but also higher-order radially symmetric terms. The focus error may be subtracted (since no provisions are made for accurately determining the test mirror's radius of curvature), but the higher-order errors will remain to corrupt the desired data. Lateral errors cause chiefly tilt terms, but also higher-order odd-powered terms. Tilt and cubic terms may be subtracted since they are not likely to arise during the diamond-turning process. Again, higher-order terms remain to corrupt the desired surface data. These higher-order surface errors are not just artifacts of the limited number of data points used in the numerical integration, but arise also in analytical modeling of the HOST process. The errors are caused by differences, between alignment and surface errors, in the reflected beam positions.

Peak-to-valley surface errors for modeled longitudinal and lateral errors are shown in Figures 4 and 5. It is seen that errors of approximately 1 millimeter are permitted for each misalignment, although somewhat larger lateral position errors may be allowed. The modeling process takes into account the change in laser beam height on the test mirror as a function of misalignment. For the 1 mm displacements and the spherical mirror used here, these beam position errors are of little consequence (for mirrors tested near the center of curvature). Sensitivity to these errors changes considerably depending on the f/number and surface figure of the mirror under test. For comparison, results are shown in Figures 4 and 5 for a parabolic mirror with the same first-order properties as those given above. It is seen that the alignment sensitivity of each test must be evaluated and the HOST position must be determined accordingly.

Figure 4. Peak-to-Valley Surface Error Due to Longitudinal Displacements

Figure 5. Peak-to-Valley Surface Error Due to Lateral Displacements

All data shown in Figures 4 and 5 used 21 points along a diameter in the x-direction. The following additional values were used to simulate the HOST setup: $\epsilon_x = 19$ mm, $\epsilon_y = 0$, $\sigma = -254$ mm, $\omega = -283.8$ mm. Eight power series terms (y^0 to y^7) were fit to the surface errors, and y^0 through y^3 were then subtracted. Peak-to-valley and rms values refer only to data along the linear scan, and were not extrapolated to the entire mirror surface. The tolerances are summarized in Table 1.

Table 1. HOST Test Sensitivities (Piston, Tilt, Focus, Coma subtracted)

Type of Error	Tolerance
Inherent instrument (1/20 wave surface figure error)	
Encoder noise	5 arcsec
Micrometer noise	1 micron
HOST longitudinal displacement	1 mm
HOST transverse displacement	3 mm
HOST constant angle offset	2.5 mrad

5. EVALUATION

Several reference spheres were first tested in the HOST prototype demonstration. Although angular sensitivity is the primary measurement for localized slope, integration of data across the optical aperture or azimuth perimeter was of greater concern. The accumulation of small errors in many scanned systems can lead to a serious overall error when measuring form accuracy. Therefore, it was decided to use reference spherical optics that could be independently verified and selected aspheres for the demonstration testing. Most of the testing was performed on-machine in order to use precise positioning capabilities; however, testing of a glass reference sphere and a 400 mm diameter parabola were made on a standard optical bench.

One of the first tests was to evaluate an alignment sphere manufactured on the diamond turning machine. Figure 6 shows the results of a horizontal scan through the center diameter of a 50 mm diameter optic. The HOST predicted P-V surface error is less than 0.2 waves, but has a somewhat different shape than the phase measuring interferometer (PMI) reference measurement.

Several other measurements were made on diamond turned and polished glass spheres. Also, measurements were taken on an aspheric (Ogive) surface which is caused by misalignment of the diamond tool with respect to the spindle centerline. As will be described later, the reason for investigating this type of surface was to provide data for compensation of setup errors. Figure 7 shows the Ogive surface error from a sphere. Coma errors were detected during this phase of the testing and were removed since the diamond turning process tends to produce axisymmetrical errors.

Tests of a 400 mm diameter $f/1.5$ parabola were made off-machine with the HOST. The data indicated that the optic was accurate to between 0.36 and 0.55 waves P-V. A subsequent null test with a large retro flat showed that the mirror was better than 0.5 waves P-V. Alignment errors were still present in the 0.5 wave determination.

At this point in the evaluation, several improvements were made to the HOST and data gathering software. The measurements with spheres showed that HOST data was accurate only to about 1/3 wave, and several causes for the lack of agreement were identified and then investigated. Diffraction effects from the diamond turned surface were felt to be impacting the ability to accurately centroid the return spot. Also, if the detector is located conjugate to the source pinhole,

Figure 6. Diamond Turned 50 mm Diameter Sphere

Figure 7. Evaluation of Ogive Surface Tested as a Sphere

several beams are possible due to multiple reflections from the detector. In measurements from the polished glass sphere, multiple reflections occurred when the beam struck the back surface and caused an additional beam traveling very close to the return from the front surface.

Movement of source/detector from conjugate positions corrected much of the multiple reflection problem. Apertures were introduced to correct diffraction related problems from low f/# diamond turned optics. To improve the stability of the centroiding process, a neutral density filter was introduced which lowered the reflected beam intensity from diamond turned optics. Data from the enhanced system was used to compensate repeatable errors introduced by the diamond turning process.

6. COMPENSATION OF REPEATABLE ERRORS

A primary reason for measuring optical components on diamond turning machines is to compensate for repeatable errors in the fabrication process. These include errors in the machine setup, tool waviness and incorrect radius compensation, centrifugal bending of the mirror as it is spinning, and Abbe offset in the machine axes movement. An experiment using the HOST was conducted in which deliberate errors were introduced to the mirror that would be typical of the present diamond turning process state-of-the-art. HOST measurement data were then used to modify the NC program which generated the optical surface. The mirror was recut as a sphere and measured both with a reference PMI and the HOST to verify compensation of the error.

Figure 8 shows a Ogive surface caused by a decenter setup error on an 60 mm diameter, f/4 mirror tested as a sphere by the HOST and phase measuring interferometer. The HOST compensated sphere data are shown in Figure 9.

A similar test was conducted by analyzing an ellipse. The diamond turning machine first cut an accurate sphere, measured by the HOST at 0.15 waves P-V and the PMI at 0.11 waves P-V. Immediately afterward, the spherical surface was machined into an ellipse with conic constant -0.1 (this provides about 1 wave departure from the desired sphere). The HOST measured ellipse is shown in Figure 10 and shows the expected 0.14 wave P-V surface. PMI verification for the ellipse was not straightforward and was not obtained. The compensated surface is shown in Figure 11. An imperfect compensation (also verified by the PMI) was caused by the omission of the polynomial term in the fitting and numerical controller reprogramming operation. A linear term was fit to the data from the above described Ogive test and was not accounted for in the compensation program. Subsequent calculations using the proper polynomial terms have explained the residual error in the optical figure.

Figure 8. Ogive Error Tested as a Sphere

Figure 9. Compensated Ogive Surface

Figure 10. Evaluation of Elliptical Surface

Figure 11. Compensated Ellipse Tested as a Sphere

7. SUMMARY & CONCLUSIONS

HOST evaluation data indicate that the scanning Hartmann test adaptation is a useful tool for measuring aspheric optical components manufactured on diamond turning machines. It is now possible to characterize otherwise difficult to test optics. Importantly, the data is easily incorporated into machine control programs for compensating repeatable errors in the fabrication process, and has promise for in-process feedback control applications. Surfaces with up to a wave of departure from an easily tested sphere were successfully compensated to under 0.2 waves.

The HOST adaptation of the classical Hartmann test to function with modern diamond turning machines features the ability to use non-uniform spacing of data points with polynomial fitting of the output data that correctly describes typical process errors. Simulation results predict that the instrument's accuracy is insensitive to longitudinal and lateral misalignments on the machine.

Elimination of diffraction effects in the HOST measurement process enhanced the accuracy from around 1/3 wave in early evaluations to 1/8 wave (0.08 μm). In prototype form, the HOST proved the metrology concept for the diamond turning application but was hampered by a slow and involved data taking process. As a result, mostly low resolution (21 point) scans were used and relatively few measurements were generated. Full automation of the device will alleviate many of these problems. The ability to make rapid scans is necessary for more accurate positioning on the diamond turning machine, and a streamlined data reduction procedure will provide a smoother interface for compensation of repeatable process errors.

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