Using Linear Variable Differential Transformers and Ultrasonic Transducers to measure flatness and parallelism for NIF Optics

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ABSTRACT

Measuring surface figure of large ground surfaces has been done with infrared interferometers or by means of local measurements with a spherometer to obtain a general shape of an optical surface. This paper describes a straightforward technique to obtain surface figure of plano parallel optics with an array of transducers referenced to an optical flat. The instrument utilizes 16 linear variable differential transformers (LVDT) and 16 ultrasonic transducers (UT) to measure surface figure of side 1, side 2 and the wedge in one measurement setup. The transducers are setup in a 4 x 4 array, for a total of 32 in one fixture. The data is acquired via a PC acquiring data through serial ports and an A/D card. The two 4 x 4 data sets are fit to the first ten Zernikes using the method of least squares. The data is displayed with 3D graphics to obtain a view of the optical surfaces. By using 14 bit digital LVDT’s and employing the cross correlation technique for acoustic signal processing a system accuracy of ±1.0 μm for the LVDT array and ±2.75 μm for the UT array has been achieved.

Keywords: Ultrasonic Transducer, LVDT, Cross Correlation, Acoustic Signal Processing

1.0 Introduction

The National Ignition Facility (NIF) requires thousands of high precision optical components to be manufactured at high production rates of several optics per day. With this requirement the processes used to manufacture these elements must minimize the amount of time in polishing. For NIF optics there are three manufacturing processes prior to polishing that require knowledge of surface figure before interferometry can be used; rough generating, ELID (Electrolytic In-process dressing) grinding and pre-polishing. To reduce manufacturing time and handling this system of discrete measurement points is used to give the machine operator an accurate description of the ground or polished surface. The driver behind this system is the requirement to have <16 μm of wedge in parts from 2600 to 3700 cm² in area after final grinding. Typically surfaces from final grinding, and in this case, ELID grinding will not have form errors any higher order than astigmatism other than rolled edges from intermittent cut effects. To be able to quantify these aberrations 16 discrete points were designed into a lightweight fixture to sample the surface with as much coverage as possible. The LVDT array has about 4 times the accuracy as compared to the ultrasonic transducers, so the purpose for each array is two fold. The LVDT’s will measure surface figure for ground and polished pieces and the UT’s will measure wedge and figure for ground surfaces and wedge for polished surfaces. Each process will make machine parameter adjustments in order to reduce surface figure error and wedge based on the measurements.

1.1 Hardware Description

The LVDT selected is a Solartron Metrology digital probe. The main reason for selecting the Solartron transducer was the off the shelf ability to multiplex up to 32 transducers. Also, with 14 bit resolution they give the desired measurement accuracy. An optical flat was manufactured to be used as a reference for the LVDT array. It was polished flat to approximately 0.4 λ p-v. The Ultrasonic Transducers are Krautkramer Branson 20 MHz KBA 125 contact type transducers operated by a standard Krautkramer Branson CL304. Each ultrasonic transducer is multiplexed to the PC with a Kiethly High Density switch system model 7001. The acoustic signals are digitized with a GAGESCOPE model 8500 A/D card for signal processing to determine thickness. The lightweight frame was designed to minimize self weight deflection as well as giving a stable platform for the transducers (Figure 1). The optic is supported on a 12 point whiffle tree mount giving the optic uniform support during testing. The mount also acts as a means of distributing the load of the instrument during test.
A program written in Visual Basic controls the instrument. There are several command buttons that allow an operator to control the acquisition of the LVDT system and the ultrasonic system. The program displays each surface plot in a 3D format as well as surface statistics.

(Figure 1. Above: Lightweight fixture. Transducers are not shown. Below: View of Ultrasonic transducer in fixture)

1.2 Measurement Sequence

Each optic is loaded into the support mount and left to stabilize for 30 to 60 minutes before testing. Phosphate laser glass has a high coefficient of thermal expansion, 13.4 ppm/K, so the proper settling time essential for accurate measurements. The resting place for the instrument is on an optical flat which is the reference for the LVDT array. The ultrasonic transducers require an acoustic couplant, so an index matching oil is used and placed on the optic with the aid of a template. The 16 reference points are acquired and the fixture is lifted and placed on the optic under evaluation. The instrument itself weighs approximately 8 pounds, so moving on and off the reference is easy. Next, the 32 points for the optic are acquired; the LVDT array will measure the top surface and the ultrasonic transducer array will measure the relative thickness. The reference is subtracted from the LVDT values and the first 10 Zernike polynomials are fit to the 16 points. The LVDT values are then subtracted from the thickness values and the same Zernike fitting is performed for the thickness values. Piston and tilt are removed for both top and bottom surfaces. The wedge in the surface is defined by the second and third Zernike term calculated from the thickness data.
2.0 Data Processing

To represent the surface shape when measuring surface heights with a 4x4 rectangular grid one would like to use a general third order function. For example, there are ten polynomials with combinations of x and y with a total power less than or equal to 3 that could be used. The first ten Zernike polynomials (piston, x-tilt, y-tilt, focus, 0-degree astigmatism, 45-degree astigmatism, 0-degree coma, 90-degree coma, 0-degree trefoil and 90-degree trefoil) could also be used. Any complete set of functions could be used equally well. The different sets will give different coefficients but the resulting best-fit function will be the same. If a set of functions is orthogonal, then the best-fit coefficient of each function is independent of how many functions are being fit. In this case the Zernike's are not orthogonal. But, since they include all third order functions, the same result would be achieved if an exotic set of polynomials designed to be orthogonal on a 4x4 grid was used5.

The 16 points acquired from the LVDT's are fit to the first 10 Zernikes using the method of least squares. The fit will be affected by the ability of Zernikes to represent the surface shape. Zernike representations of the measured surface were calculated and show good agreement with the raw data (figure 2). The raw data are the values measured by the LVDT array subtracted from the reference, the fit_surf plot is the result of the Zernike fitting. The p-v and rms for the raw data set is 4.7

\[ \text{Unfit Residual (amplitude in microns)} \]

\[ \text{fit_surf} \]

(Figure 2. Comparison of raw data to Zernike representation.)

The 16 points cover about 90% of an amplifier slab which is 808mm x 458mm. To obtain a full aperture representation the data is extrapolated to a 21x35 grid. The data represented is from an amplifier slab that is in process in the NIF facility. The data obtained from this instrument compares to within 1.0 μm p-v with interferometry. The data from this instrument is compared to interferometry to evaluate the system performance, it is not an attempt to suggest it is as accurate. The interferometer aperture does not cover the entire optic on this data so this will contribute to part of the

\[ \text{μm and 1.3 μm and the fit surface is 3.87 μm and 1.1 μm respectively. The unfit residual map is 0.356 μm rms (figure 3).} \]

(Figure 3. Unfit residual map)
differences seen in amplitude, 0.5 μm, and shape. Most of the difference is due to mount distortion, fixture repeatability and unfit residuals. The LVDT surface is 4.2 μm p-v (figure 5) and the interferometer data (figure 4) is 2.8 μm p-v.

2.1 Ultrasonic Transducer Data Processing

Ultrasonic thickness measurements are used for many different applications, determining material properties, flaw detection and thickness measurements\(^2\). The application here is to measure relative thickness with 16 different transducers. This is done by determining the time delay between two successive echoes. The problems associated with absolute thickness measurements are not relevant here. However, there are some problems associated with this approach that need to be realized.

1) Time of flight (TOF) measurement accuracy is 100 to 200 Pico seconds.
2) Differences in transducer construction require calibration.
3) Couplant and transducer placement accuracy.
4) Material homogeneity.

When acoustic energy is introduced into the part with a contact type transducer, several acoustic reflections occur at the boundaries of the optic. Depending on the attenuation properties of the material several back wall echoes can be recorded. By selecting the multi-echo mode, to first order, couplant effects will be eliminated. Once the echoes have been digitized (figure 6) an in-window time delay can be calculated by using the cross correlation function\(^3\).

\[ \text{Corr}(g,h) = \int_{-\infty}^{\infty} g(\tau+t)h(\tau)d\tau \iff G(f)H^*(f) \quad \text{Correlation Theorem} \]

Functions g(t) and h(t) are the first and second back wall echoes, G(f) and H(f) are their fourier transforms. By performing the conjugate multiplication and transforming back to the time domain the output will have a maximum corresponding to the in-window time delay (figure 7). The maximum is found by fitting a third order polynomial to a section located at the peak. By locating the point at which the slope is zero of the polynomial the time delay can be found.

\[ \frac{dy}{dt} = C_1 + 2C_2 t + 3C_3 t^2 = 0 \]

Although there are other methods, such as zero crossing, phase slope, etc., this technique was chosen because it is less sensitive to differences in specific features in the echo affected by distortion and low signal to noise. Once the in-window delay is known the thickness, T, can be calculated with the knowledge of the acoustic velocity, AV. T=TOF*AV/2. The acoustic velocity can be calculated or measured, since this is a relative measurement absolute accuracy of the acoustic velocity is not required. For phosphate laser glass the calculated velocity is 184.00 in/sec and the measured velocity is 187.000 in/sec. The difference in values is the lack of knowledge in material properties (E is the Modulus of elasticity, p is the density and μ is Poisson’s ratio.

\[ \text{Acoustic Velocity} = \frac{E}{\rho} \frac{1-\mu}{(1+\mu)(1-2\mu)} \]
As mentioned before, by using the multi-echo mode couplant affects and placement errors are eliminated. However, there are second order effects that alter the time of flight by several nanoseconds. This has imposed the need to calibrate the time of flight for each transducer. Each transducer was placed on the same block of material (figure 8) and the time of flight recorded. The differences were calculated and stored for subtraction during data acquisition.
The transducer itself is spring loaded into a cylinder that is held in a kinematic support. A deterministic support is used to minimize the transducer to transducer couplant variations as well as the alignment of the transducer to maximize signal strength. Repeatability tests were performed on 41mm and 90mm thick parts to determine what the effect of assumed thickness would be. The results showed a thickness measurement accuracy of ±1.2 μm.

<table>
<thead>
<tr>
<th>Single Point Repeatability</th>
<th>Placement repeatability</th>
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<tbody>
<tr>
<td>1σ (Pico seconds/μm)</td>
<td>1σ (Pico seconds/μm)</td>
</tr>
<tr>
<td>90.0 / 0.42</td>
<td>380 / 1.2</td>
</tr>
</tbody>
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Changes in temperature and surface finish have also been calibrated as a function of time of flight for phosphate (figure 9 and 10) and just temperature for BK7. With the proper thermal relaxation, temperature calibration is not used since this is a relative measurement and thermal gradients are at a minimum unless material removal information is required. The system is equipped with a thermocouple to monitor part temperature. Surface roughness calibration as well is only used when material removal information is required. Three different parts of phosphate were manufactured from the same block to eliminate material differences for this calibration. Each block was prepared with an ELID/ELID surface, ELID/Polished and Polished/Polished. The effect of the transducer being on the ground side or the polished side was not significant for this calibration.

(Figure 9. Surface Finish Calibration normalized to a polished surface. Error bars shown are ±1σ)

(Figure 10. Temperature Calibration.)

The result for measuring wedge with the ultrasonic transducers is compared with interferometer data and the figure is compared to an LVDT measurement. The interferogram shown is a fizeau interference pattern masked to a circular aperture. The aperture size is known and fringes are counted to calculate the angle. The amount and direction is calculated...
to based on knowledge of the part dimensions and the test configuration. The amount of wedge calculated is 8.4 \( \mu m \) p-v (figure 11) and the amount measured by the ultrasonic transducers is 12.2 \( \mu m \) p-v (figure 12).

(Figure 11 Fizeau pattern from an amplifier slab)

UT Wedge Measurement (amplitude in microns)

(Figure 12 Ultrasonic measurement of wedge)

Surface two as measured by the ultrasonic transducers is compared to the LVDT measurement of surface two. The LVDT measurement represents a ground surface and is 19.4 \( \mu m \) p-v (figure 13). The ultrasonic measurement of the same surface is 22.25 \( \mu m \) p-v.
LVDT Measurement (amplitude in microns)

(Figure 13. Above is the LVDT measurement. Below is the UT measurement.)

UTG Measurement (amplitude in microns)

3.0 Conclusion

The purpose of this instrument is to measure figure and wedge of ground parts. By utilizing standard transducers and creating a data acquisition system micron type accuracy has been achieved. Each LVDT by itself has sub-micron accuracy. When 16 are multiplexed together and used in an array to map surface figure their total system accuracy is ±1 μm. That includes optic mount distortions, instrument distortions and unfit residuals. The ability to measure the time of flight of acoustic reflections in thicknesses from 40 to 90 mm has been achieved to micron accuracy. When 16 are multiplexed together and used in an array to map surface figure their total system accuracy is ±2.75 μm. That includes optic mount distortions, transducer placement error and unfit residuals. This is done by being able to resolve the time of flight of acoustic pulse to sub-nanosecond accuracy. This measurement technique has proven to be an efficient means of determining surface figure of ground and polished parts to implement significant improvements in fabrication process development.
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References:


5. Notes from Paul Glenn.