PHASE-SHIFTING DIFFRACTION INTERFEROMETER FOR INSPECTING NIF IGNITION-TARGET SHELLS

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OVERVIEW OF THE DESIGN

This paper describes the top-level design of a phase-shifting diffraction interferometer (PSDI) system for mapping the outer surface of small spherical parts (a shell), with emphasis on the PSDI head and the motion control system used to position it with respect to a shell. The method of operation of the PSDI, which consists of a laser front-end and an interferometer head, is described extensively elsewhere [1, 2, 3] and a brief description is included at the end of this paper. The interferometer head is adapted to an XYZ linear stage stack, and the shell to be measured is held by vacuum in a transfer chuck mounted to a Theta-Phi rotary stage stack (elevation-azimuth, relative to the shell). Figure 1 shows a model of this system, and Figure 2 shows a detail from that model.

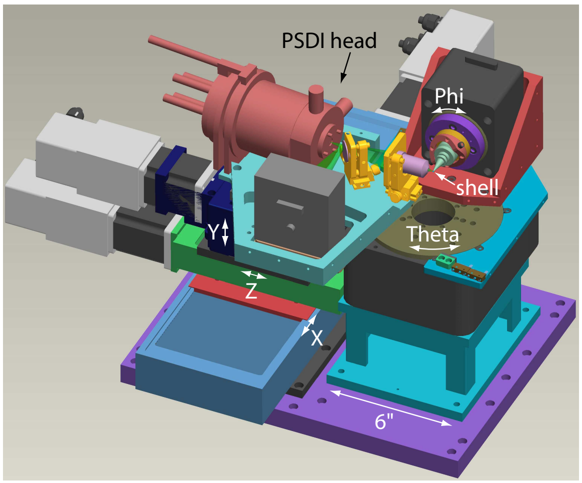

FIGURE 1. Model of the PSDI head mounted to the XYZ linear stage stack and measuring a shell held by a transfer chuck mounted to the Theta-Phi rotary stage stack.

Closed-loop computer control of the stages allows positioning the interferometer relative to the shell and then orienting the shell to measure a particular portion of its surface. The rotary stages allow mapping one half of the shell surface (hemisphere), then the shell is flipped end-for-end so that the other hemisphere can be mapped. Transfer chucks are used to mount the shell in the system, minimize handling of the fragile shells, and to facilitate flipping of a shell. The first system will be tested with a manual part loading and flipping system in September 2006, and is extendable to a future fully automated system for handling shells.

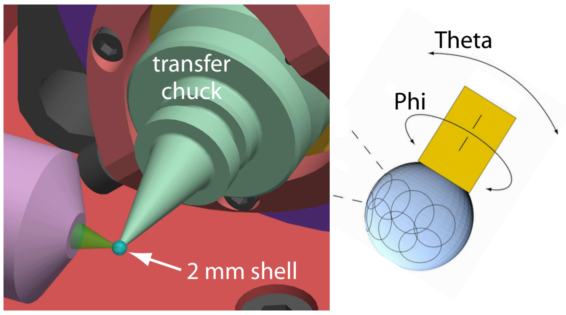

FIGURE 2. Detail of the shell, transfer chuck, and convergent rays from the PSDI head (left). Depiction of overlapping measurements on a shell surface (right).

The five motorized stages used to position the PSDI head and shell relative to each other are controlled by an Aerotech Automation 3200® machine tool controller using a LabVIEW™ user interface. The control system operates in a point-to-point position and hold mode: first positioning the PSDI head relative to the shell to acquire and center the fringe pattern, then indexing the shell after a measurement is made. The converging rays from the microscope objective in the PSDI head form a cone with a 20° included angle and its vertex at the center of the shell. Each measurement requires 3 seconds and consists of eight individual measurements averaged together. An entire hemisphere can be mapped with approximately 50 measurements, leading to 150 seconds to perform the measurements-only for a hemisphere. Additional time is needed to index the rotary stages and re-center the fringes if necessary, as well as time for data authentication and file management. Assuming that the data analysis can be performed either in parallel with the

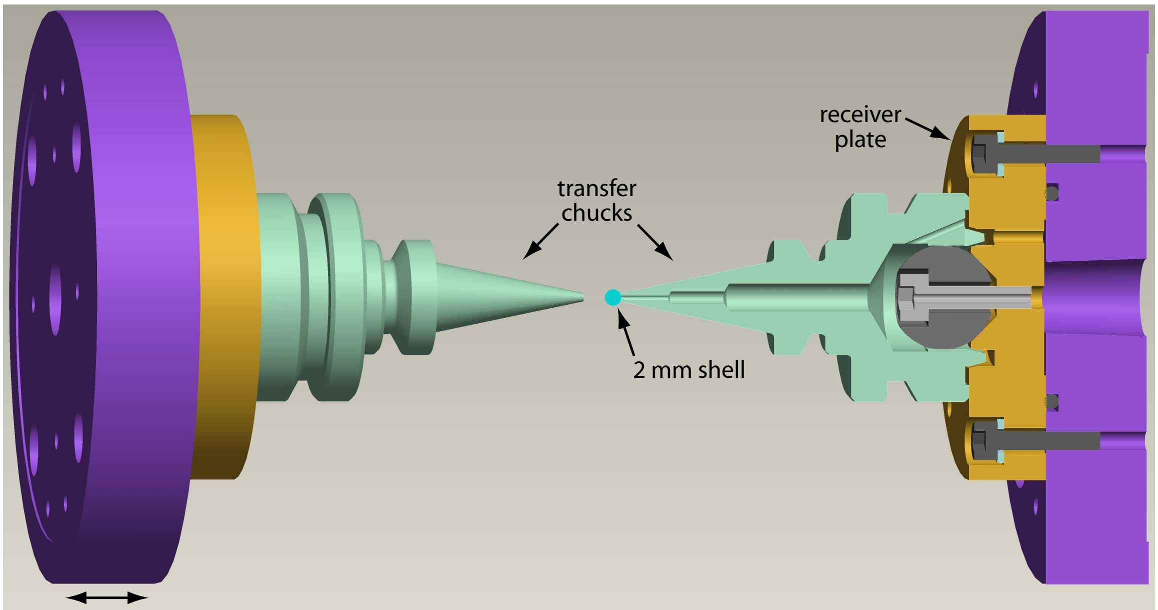

FIGURE 3. Model of two transfer chucks and their receiver plates, positioned to flip a shell. The cross-section reveals the interfaces between a chuck and receiver plate.

next measurement or off-line, a rough estimate for measuring an entire hemisphere is 7.5 minutes if each measurement, indexing and re-centering of the stages, and file management step requires 3 seconds. The five computer-controlled stages can handle that speed, but clearly the bottle neck would be manual data verification, organization, analysis, and archiving. In the near future, the user interface for the five motorized stages will communicate with an LLNL-written supervisory program that commands those stages and coordinates them with the legacy LLNL software package used to control and coordinate phase-shifting in the laser front-end and the frame grabber card for the camera. The supervisory program will also coordinate with a second legacy LLNL software package that is used to authenticate and analyze the acquired data, and will perform data organization and archiving.

Figure 3 shows a model of two transfer chucks and their respective receiver plates. A slip fit between a hardened-steel sphere and the diamond-turned bore in the transfer chuck provides the radial constraint for the chuck. The annular land on the back of the chuck mates with a diamond-turned flat surface to provide the axial and tilt constraints for the chuck and a vacuum seal. The annular protuberance at the back of the chuck is for piloting the chuck onto the receiving plate; protecting the critical diamond-turned surfaces. A source of vacuum is provided along the centerline of the receiving plate. A pressurized hood (not shown) engages the front-most groove on the transfer chuck to allow removing the chuck from its source of vacuum in the rotary stage stack and transporting it. The rear groove on the chuck accommodates a secondary, mechanical means for securing the chuck to the receiver plate, and will facilitate future automated handling of the transfer chuck. Flipping the part end for end is accomplished by positioning the receiving chuck as close as reasonably possible — using a vision system for displacement feedback — to the shell being held by the sending chuck. Vacuum is then applied to the receiving chuck and removed from the sending chuck. To first-order for a 2 mm diameter shell, a translational eccentricity between the two chucks (non-coincidence of the centerlines) causes a rotation of the shell of approximately 1 mrad for each 1 μm of eccentricity. Rotation of the shell during its flight between the chucks can add to the net rotation.

The error budget for the combined PSDI head positioning system and shell mounting system (transfer chucks) is based on a requirement that an acceptable fringe pattern is retained if the center of the shell stays within a 20 to 50 μm sphere of uncertainty relative to the PSDI head. Errors leading to the uncertainty in the knowledge of the angular orientation of each measurement site

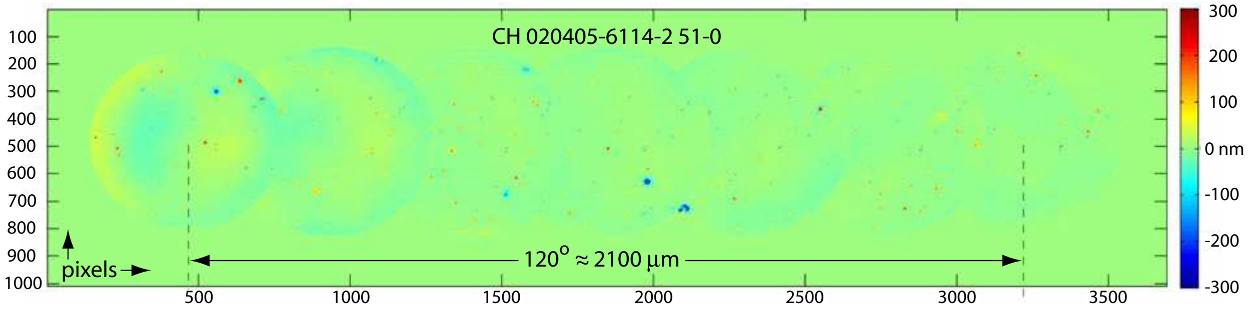

FIGURE 4. Measurement data produced by a demonstration-version of the phase-shifting diffraction interferometer. The seven overlapping measurements span one-third of the surface at the equator of this 2 mm diameter shell.

with respect to a landmark on the surface of a shell is accommodated by using observed features on the surface to stich the data together to form an accurate mosaic surface map of the shell. In this regard nature helps us, since a featureless surface is not a concern in the first place. The acceptable amount of uncertainty in knowing the angular orientation of each measurement is still being traded off against the burden on the search algorithm that stitches the measurements together, and is believed to be acceptable for the design presented.

MOTIVATION FOR DEVELOPING THIS INSTRUMENT

The application of this interferometer to the characterization of target capsules (shells) for Inertial Confinement Fusion (ICF) is due to the requirement that the surfaces of these capsules be extremely smooth and free of defects over the entire surface. Many capsules which are smooth enough on average have local defects which render them unacceptable for ICF. Figure 4 shows an example of measurement data produced by a demonstration-version of the interferometer, revealing unacceptable surface defects. Measurements such as the one shown in Figure 4 have already provided feedback needed to improve the manufacturing process for capsules. The interferometer described in this paper will provide much improved coverage much more rapidly to enable additional process improvements and will provide the throughput needed for efficient quality control of the capsules that will be used in the Ignition Campaign with the National Ignition Facility (NIF) [4]. The need for characterization over 4π steradian makes the PSDI coupled with the computer-controlled mechanical stage system described here an ideal choice for this application. An entire hemisphere of the capsule can be mapped with a lateral resolution of one micron and a height resolution of a few nanometers without handling the shell. With a single flip of the shell the entire surface is mapped. In addition, this instrument will be used to characterize inner surfaces of pieces of sacrificial shells. Furthermore, the instrument allows measurement of the radius of a shell to an accuracy governed by the mechanical stage that controls the focus direction (Z), which is within ± 2.0 μm for the unmapped system and can be improved to the sub-micron range by calibration with an artifact.

METHOD OF OPERATION OF THE INTERFEROMETER

An advantage of the optical design of this interferometer is the use of a spherical reference wavefront. The front-end of the interferometer consists of a short coherence-length laser that produces a polarized beam that is resolved into two co-linear beams having orthogonal polarizations. One of the beams passes through a delay line having a length greater than the coherence length of the laser and becomes the reference beam. The reference beam is recombined with the other (measurement) beam, and both are transmitted through a single-mode optical fiber to the back end of the fiber coupler in the interferometer head. Figure 5 shows a model of the PSDI head. Upon exiting the polished end of the fiber in the fiber coupler the beams produce a spherical wavefront that is focused onto a pinhole, which produces a more perfect spherical wavefront through diffraction. A scraping mirror sends

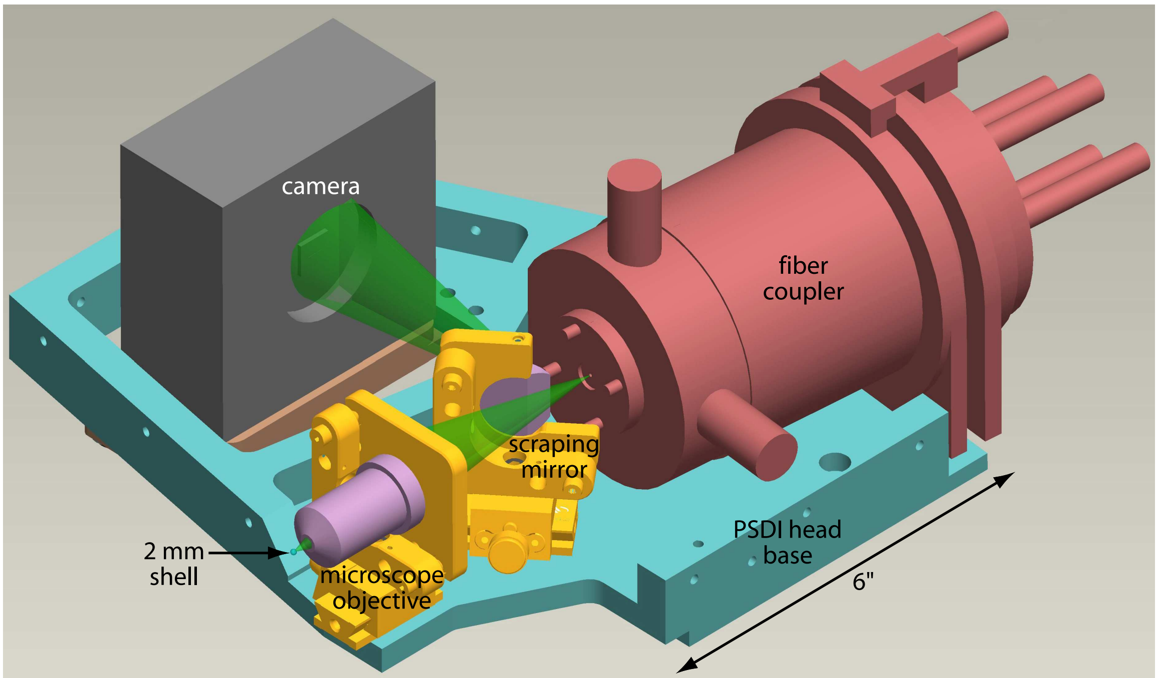

FIGURE 5. Model of the PSDI head showing its main optical components and the ray bundles emanating from the pinhole in the fiber coupler.

a portion of the combined measurement and reference wavefronts to a CCD camera, while the remainder of the combined beams are focused by a microscope objective onto the spherical surface being measured. The reflected beams from that surface are recombined with the two beams that were diverted earlier by the scraping mirror, and sent to the camera. Starting at the pinhole, the difference in optical path lengths for the two pairs of beams reaching the camera is equal to the length of the delay line in the front-end. The measurement beam from the test object and the reference beam from the scraping mirror are coherent and therefore interfere with each other. By phase shifting the reference beam relative to the measurement beam in the front-end, the amplitude and phase of the electric field at the camera can be measured. Numerical techniques are used to propagate this field to the surface of the test part to provide a measure of surface height.

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