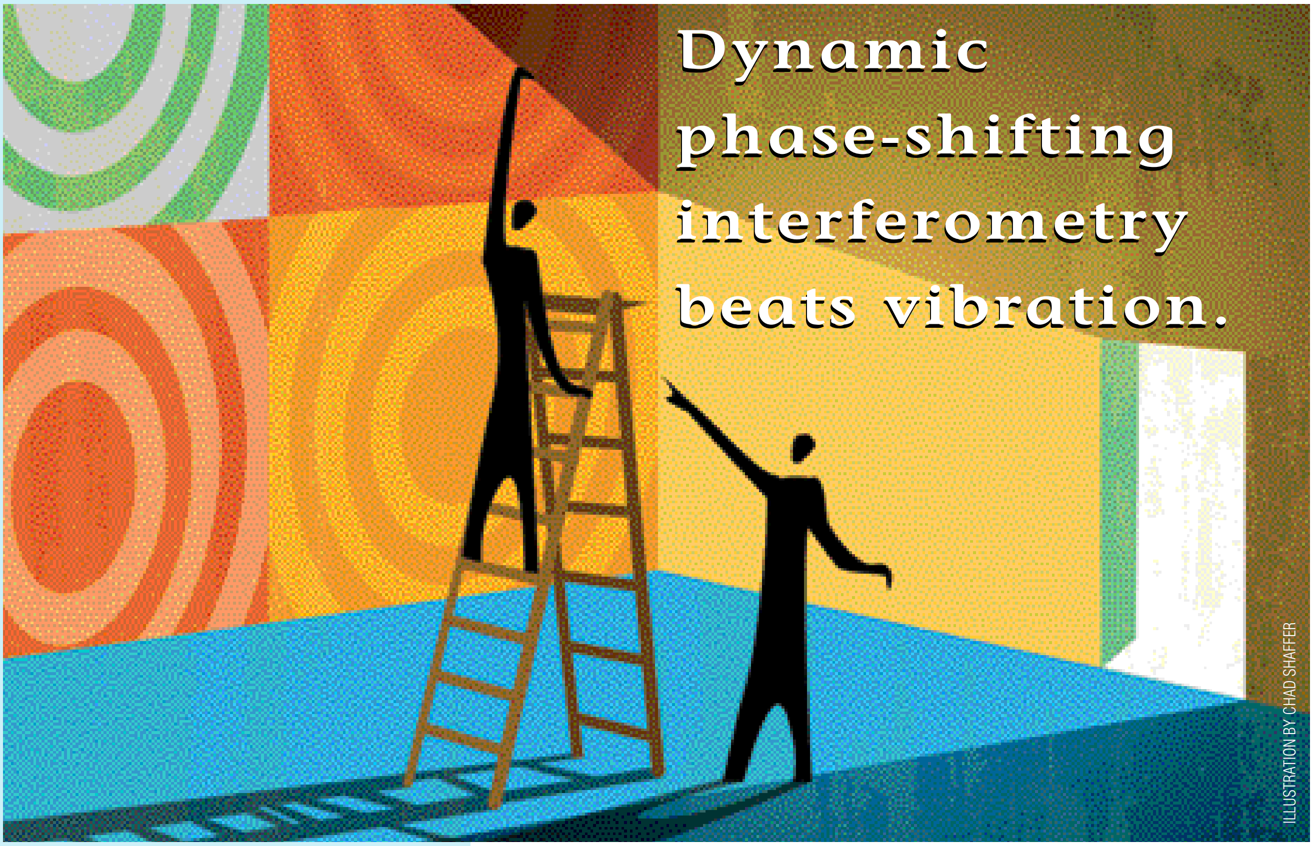

Going Through a Phase

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Interferometry is a powerful tool used in numerous industrial and R&D applications. It suffers from limitations, however, the most significant of which is that it is extremely sensitive to vibration and can be used only in a controlled environment. In addition, conventional interferometric techniques have problems measuring surfaces whose shapes change with time. Phase-shifting interferometry provides a solution. By leveraging phase-shifting techniques, researchers at 4D Technology (Tucson, AZ) and the University of Arizona (Tucson, AZ) have developed two different single-shot interferometers that work well in the presence of vibration and can measure the shapes of dynamically changing surfaces.

Phase-Shifting Interferometry

For interferometry to be useful in manufacturing applications, there must be a good method for getting interferometric data into computers where it can be be processed to provide useful information. Interferometric data contains three unknowns: the amplitude of the reference beam, the amplitude of the test beam, and the phase difference between the two interfering beams. Of these three items, the quantity of most interest is the phase difference between the two interfering beams because that phase difference gives the optical path difference. For the measurement of surface height variations, we want to measure the phase variation across the beam and then convert that data into height variations across the sample.

We can determine the phase difference between the two interfering beams by measuring the intensity of the interference fringes as the phase difference between the two interfering beams changes in a known manner. The phase typically is changed by 90° between consecutive intensity measurements. The three unknowns require us to make at least three intensity measurements. Using 90° phase steps makes the calculations easy because we measure the sines and

Phase *continued on page 21*

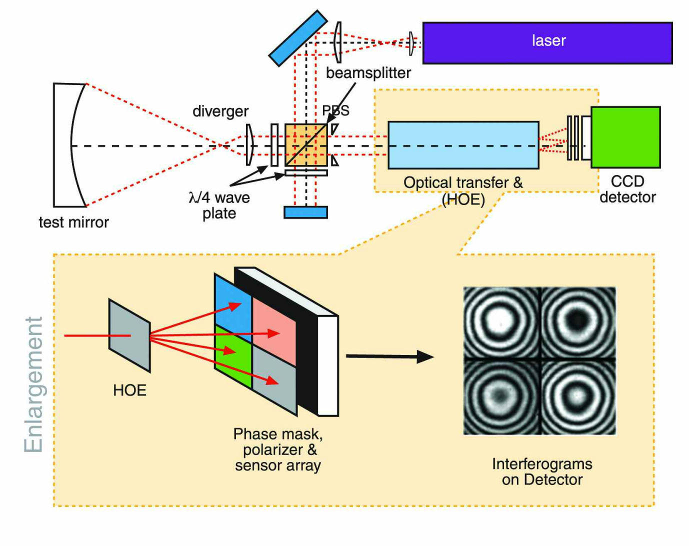

Figure 1 A single-shot Twyman-Green interferometer uses a polarization-based beam divider, holographic optical element, and phase-shifting mask to produce four separate, phase-shifted interferograms with a single detector.

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cosines of the phase difference. To reduce errors, it is best to make four or more intensity measurements instead of the minimum three measurements.

We call this technique phase-stepping or phase-shifting interferometry. In these measurements, a solid-state detector array captures the interference fringes. The output of the detector is digitized and the resultant data read directly into computer memory. A phase shifter—typically a moving reference mirror or an electro-optic modulator—varies the phase difference between the two interfering beams in a controlled manner. The phase change between detector readouts can be introduced either in a discrete or continuously varying fashion. A computer controls the phase difference between the two interfering beams and simultaneously captures the detector output. From these three or more measurements, the system can calculate the phase difference using a wide variety of algorithms.

The phase-shifting technique produces fast, accurate measurements. In addition, the mathematical sign of the error—that is, whether a point is high or low—is determined automatically. The most important factor is changing the beam-to-beam phase difference between successive intensity measurements in a controlled manner. This is where the environment becomes critical, because vibration or air turbulence can change the phase difference between the two beams in unknown ways, and hence introduce large errors in the measurement.

In a Single Shot

A better approach for reducing the effects of vibration is to capture all the phase-shifting frames at once. Several techniques exist for simultaneously obtaining four phase-shifted interferograms. Although so-called single-shot phase-shifting interferometers have been available for some time, they typically incorporate four separate CCD cameras; as a result, calibration and alignment of the individual cameras become critical to accurate results. A superior approach is to have all four phase-shifted frames fall on a single CCD camera (see figure 1).[1]

In this arrangement, a polarization beamsplitter imparts orthogonal polarization to the reference and test beams. Quarter-wave plates are placed in the reference and test beams so the beam transmitted on the first pass through the beamsplitter is reflected on the second pass, and vice versa. After the two orthogonally polarized beams combine into one, they pass through a holographic optical element that splits them again into four separate beams.

The four beams pass through a birefringent mask (phase mask) placed just in front of a CCD camera. The four segments of the birefringent mask introduce phase shifts between the test and reference beams of 0°, 90°, 180°, and 270°, respectively. Since the test and reference beams have orthogonal polarization, they do not interfere. To obtain interference, a polarizer with its transmission axis at 45° to the direction of the polarization of the test and reference beams is placed between the phase mask and the CCD array; thus, a single detector array captures all four phase-shifted interferograms in a single shot.

The short duration of the exposures mitigates the effects of vibration as well as air turbulence. The effects of air turbulence can be reduced by taking many sets of data, so that the time between the different data sets is long as compared to the time it takes for the turbulence to change; averaging the data minimizes the effect.

Using short exposures to "freeze" the vibration eliminates the effects of vibration and allows us to measure the vibrational modes of a test piece. The system can generate movies showing the vibration and measuring flow fields.

Adding Wavelengths

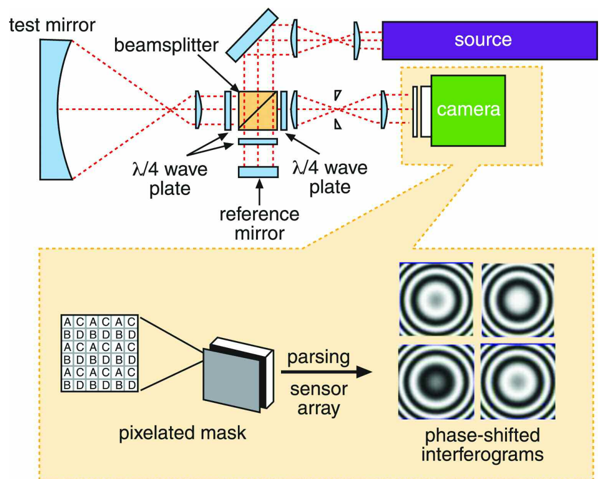

Figure 2 A Twyman-Green interferometer uses a micropolarizer phase-shifting array to capture data at more than one wavelength.

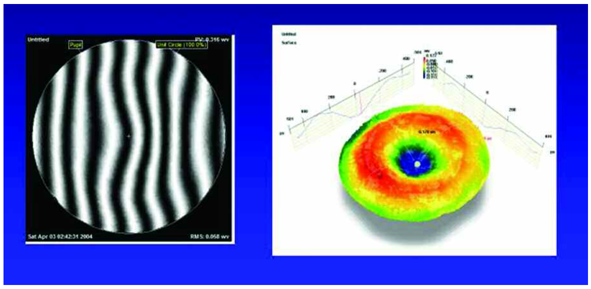

Figure 3 The robust configuration can measure test pieces on different tables from the instrument, as this data from a 309-mm-diameter, 2-m radius of curvature shows.

Although the phase-shifting, single-shot interferometer described above works well for dynamic interferometry, the holographic element used in the interferometer limits measurements to a single wavelength. Sometimes it is advantageous to use different wavelengths, or even multiple wavelengths, and at other times, wide-bandwidth sources or white-light sources are best. As a result, we need a single-shot dynamic-measuring interferometer that works well over a large wavelength band.

An approach that works well over a large spectral bandwidth is to impart orthogonal linear polarization to the test and reference beams and then to use a quarter-wave plate followed by linear polarizers at different angles to introduce the phase shifts. We orient the quarter-wave plate to convert the test beam into right-handed circular polarization and the reference beam into left-handed circular polarization. When these circularly polarized beams pass through a linear polarizer, they undergo a relative phase shift proportional to twice the rotation angle of the polarizer results.

Thus, if a phase mask consists of an array of four linear polarizer elements having their transmission axes at 0°, 45°, 90°, and 135°, and a polarizer element is placed over each detector element, the mask will produce an array of four phase-shifted interferograms (0°, 90°, 180°, and 270°, respectively. Although an achromatic quarter-wave plate could be used to extend the operational spectral range of the phase mask, the phase shift produced by the rotated polarizers does not depend greatly on the quarter-wave plate being a true quarter-wave plate.[2] A phase shifter of this type is often called a geometrical phase shifter since the phase shift remains independent of wavelength.

Using the micropolarizer phase-shifting array (see figure 2), we can build a Twyman-Green interferometer.[3] The essential characteristic of the two-beam interferometer is that the test and reference beams have orthogonal polarization and the micropolarizer array matches the CCD array. Fizeau interferometers can also be used if the reference and test beams have orthogonal polarization. Methods exist to obtain orthogonal polarization for the test and reference beams in a Fizeau interferometer. We can place a quarter-wave plate between the test and reference surfaces, for example, or introduce sufficient tilt between the reference and test surfaces so that we can use separate orthogonally polarized light beams for the reference and test beams (see figure 3). The micropolarizer phase-shifting array interferometer works well in the presence of vibration and with a wide range of source wavelengths.

Techniques such as the two single-shot methods described in this article are greatly increasing the applications of interferometry for measuring dynamic systems and for performing measurements in less than ideal environments. The combination of modern electronics, computers, and software with old interferometric techniques yields powerful measurement capabilities. **oe**

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