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 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 from page 20
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 ref-
erence mirror or an electro-optic modulator—varies the
phase difference between the two interfering beams in a con-
trolled 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 turbu-
lence 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 tech-
niques exist for simultaneously obtaining four phase-shifted
interferograms. Although so-called single-shot phase-
shifting interferometers have been available for some time,
y 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 refer-
ence beams have orthogonal polarization, they do not
interfere. To obtain interference, a polarizer with its
transmission axis at 45° to the direction of the polariza-
tion 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 turbu-
lence 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 vibra-
tional modes of a test piece. The system can generate movies
showing the vibration and measuring flow fields.

Adding Wavelengths

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.

Figure 2 A Twyman-Green interferometer uses a
micropolarizer phase-shifting array to capture data at
more than one wavelength.
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. Since the phase shift remains independent of wavelength.

Using the micropolarizer phase-shifting array (see figure 2), we can build a Twyman-Green interferometer. 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.

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References