# Dynamic Interferometry

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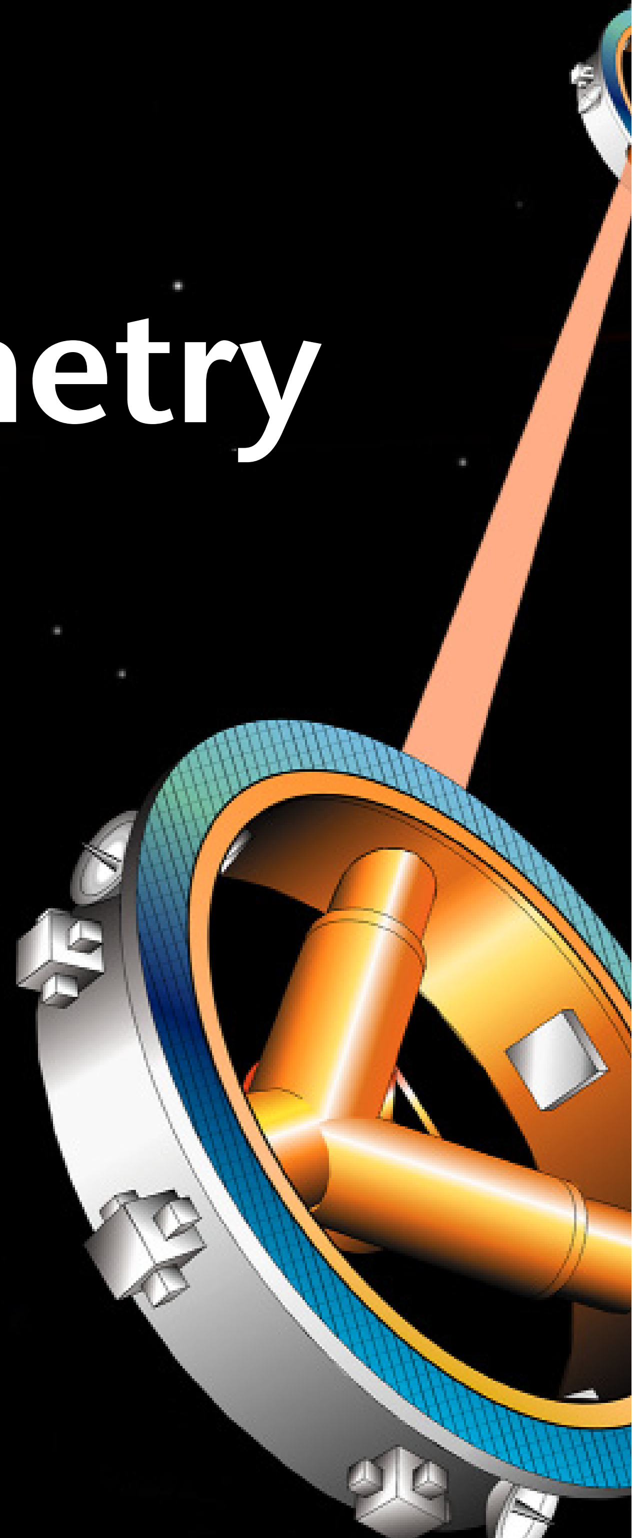
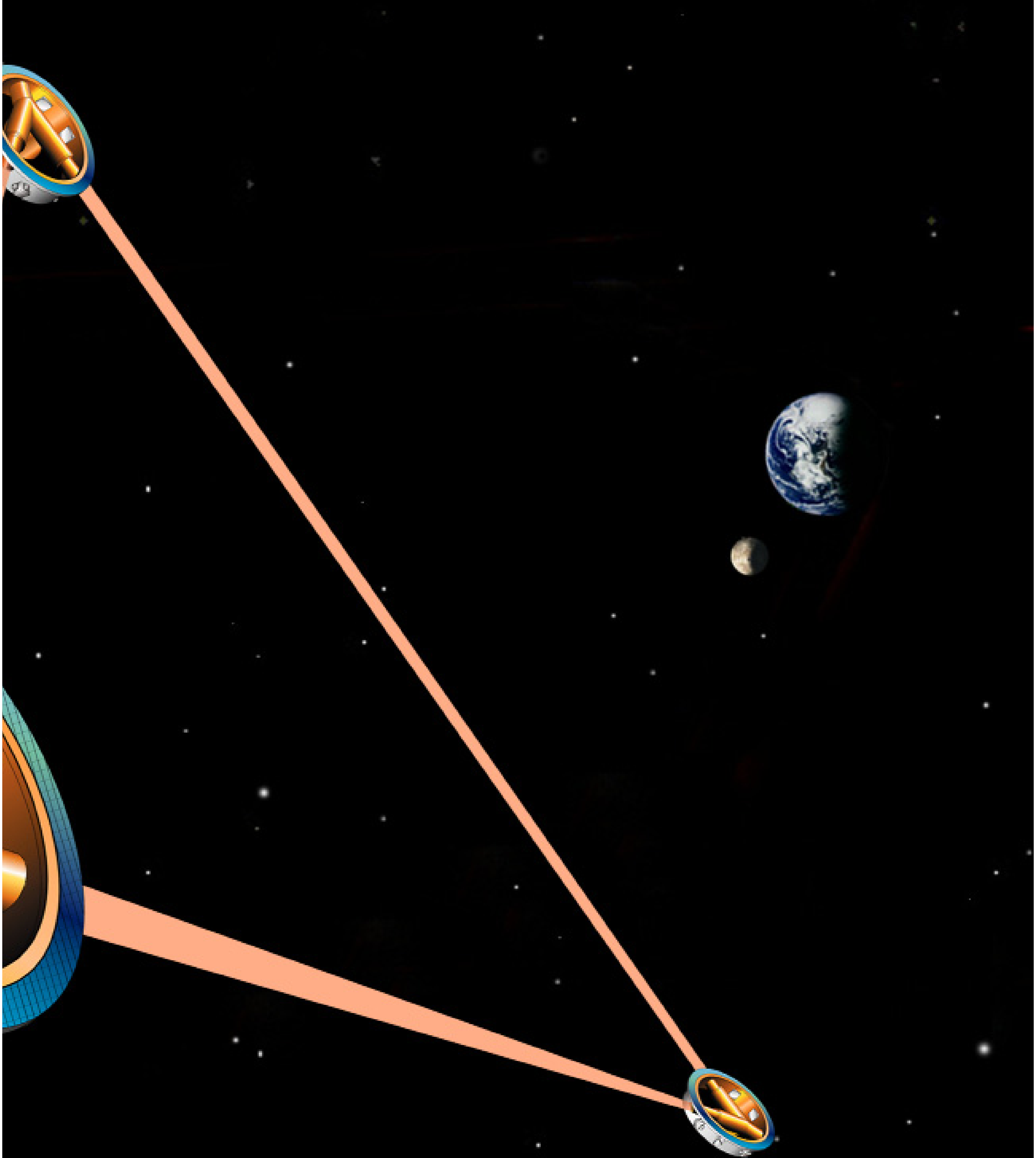
**Interferometric metrology is widely applied in research and industry. The accuracy of the measurements it provides has made it an essential component in the manufacture of a variety of items ranging from CD drives to fiber-optic systems. The author discusses ways in which the sensitivity of interferometry to environmental forces, especially vibration, can be reduced so as to increase the number of areas in which it can be employed.**





The Laser Interferometer Space Antenna (LISA) will consist of three spacecraft flying 5 million km apart. The main objective of the mission is to observe gravitational waves from galactic and extragalactic binary systems. The spacecraft will act as a giant Michelson interferometer, measuring the distortion of space caused by passing gravitational waves. Each spacecraft will contain two free-floating "proof masses." The proof masses will define optical paths 5 million km long, with a 60° angle between them. Lasers will be used to measure changes in the optical path lengths with a precision of 20 pm. If approved, the project will start in 2005 and launch in 2008. [From http://lisa.jpl.nasa.gov/whatis.html]. Great efforts are made to reduce the effects of vibration on interferometers so good measurements can be obtained. In areas such as the testing of large telescope mirrors, however, getting rid of the vibration can be extremely expensive.

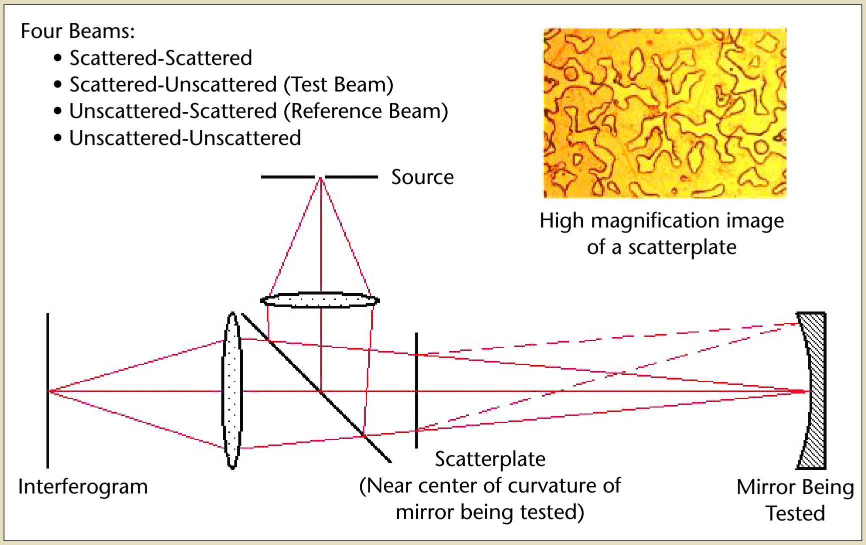



**Figure 1**. Scatterplate interferometer.

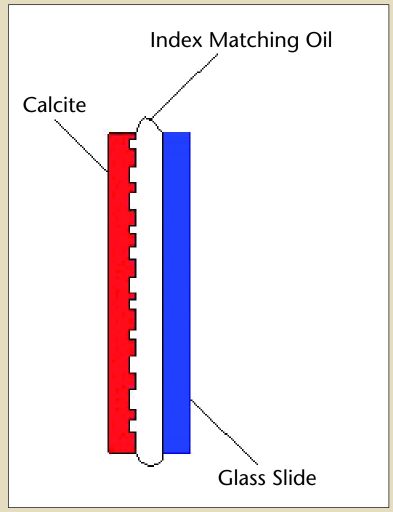



**Figure 2**. Birefringent scatterplate makes phase-shifting possible.

Interferometry is a powerful tool that is used in numerous industrial, research and development applications. These include measuring the quality of a variety of manufactured items, such as hard disk drives and magnetic recording heads, lasers and optics for CD and DVD drives, cameras, laser printers, machined parts and components for fiber-optic systems. In these applications, height variations across a sample are measured and compared to a standard. The primary reasons interferometry is so useful is that it provides superb accuracy and precision—in the nanometer or even the Angstrom range—and that it can be used to quickly measure surface shape or roughness over variable-size areas. Yet this superb sensitivity is a negative as well as a positive, because interferometry is extremely sensitive to the environment, especially to vibration. If sensitivity to vibration can be reduced without reducing the inherent sensitivity of interferometry, it is possible to apply the technique in a wider range of applications.

In this article I discuss some recent advances in reducing the sensitivity of interferometry to vibration and increasing the number of opportunities in which interferometric metrology can be applied in industrial and research settings. I discuss three techniques for reducing sensitivity to vibration: common-path phase-shifting interferometry; closed-loop feedback vibration-compensated interferometers; and single-shot phase-shifting interferometers. Before discussing decreased-sensitivity-to-vibration interferometers, a short description of phase-shifting interferometry techniques is in order, because it is the phase-shifting technique that has greatly increased the popularity and the usefulness of interferometry in industrial and research applications.

## Phase-shifting interferometry

For interferometry to be useful in manufacturing applications, there must be a good method for getting the data it generates into a computer. In interferometric data, there are 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, the quantity of most interest is the phase difference between the two interfering beams; this is because the phase difference gives the optical path difference. In the measurement of surface height variations, we want to measure the phase variations across the beam and then convert them into height variations across the sample. The phase difference between the two interfering beams can be determined by measuring the intensity of the interference fringes while the phase difference between the two interfering beams is changed in a known manner. Typically the phase is changed by 90° between consecutive intensity measurements; because there are three unknowns, at least three intensity measurements must be made. Since the sine and cosines of the phase difference are being measured, 90° phase steps are used because this makes the calculations easy. To reduce the risk of error, instead of the minimum three measurements of intensity, four or more measurements are usually made.

This technique is generally called phase-stepping interferometry or phase-shifting interferometry. In making the measurements, a solid-state detector array is used to detect the interference fringes. The output of the detector is digitized and the digitized data is read directly into computer memory. A phase shifter, such as a moving reference mirror or an electro-optic modulator, is used to vary in a controlled manner the phase difference between the two interfering beams. The phase change between detector readouts can be either discrete steps, or continuously varying. As the detector output is read into the computer, the computer controls the phase difference between the two interfering beams. From the three or more measurements, the phase difference can be calculated using a wide variety of algorithms. Measurements performed with phase-shifting techniques are fast and accurate.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In addition, the sign of the error, or in other words whether a point is high or low, is determined automatically. The most important aspect is to change the phase difference between the two interfering beams in a controlled manner between intensity measurements. This is where the environment becomes critical: vibration or air turbulence can change the phase difference between the two beams in unknown ways and hence introduce large errors in measurement.

### Phase-shifting common-path scatterplate interferometer

As discussed above, phase-shifting interferometry is especially sensitive to vibration because several frames of data are taken sequentially in time with a precise phase shift between consecutive frames. Typically, the frames are taken at a rate of 30 frames/s, with a phase shift of 90° between consecutive frames. Vibration causes incorrect measurements because it makes the phase difference between consecutive frames incorrect. Although great effort is often made to reduce vibration so good measurements can be obtained, in some instances, such as the testing of large telescope mirrors, getting rid of vibration can be extremely expensive. One way of reducing the effects of vibration is to use a common-path interferometer, in which the same vibration is essentially present in the test and reference beams, so that the effects of vibration effects nearly cancel each other out.

Although common-path interferometers are one possible solution to environmental limitations since the test and reference beams traverse the same optical path, it is difficult to separate the test and reference beams for phase shifting. One common-path interferometer that has proven to be extremely useful, especially for testing large telescope mirrors, is the scatterplate interferometer shown in Fig. 1. In the scatterplate interferometer, a scattered-unscattered test beam interferes with an unscattered-scattered reference beam. Here, the desired interference fringes result from the interference of the light of the test beam (that is first scattered and then unscattered through the scatterplate) with the light of the reference beam (that is unscattered and then scattered through the scatterplate). An approach for phase-shifting the scatterplate interferometer is to use a birefringent scatterplate to separate the test and reference beams into orthogonal polarizations and then to use an electro-optic light modulator or liquid crystal to phase shift the test beam relative to the reference beam.

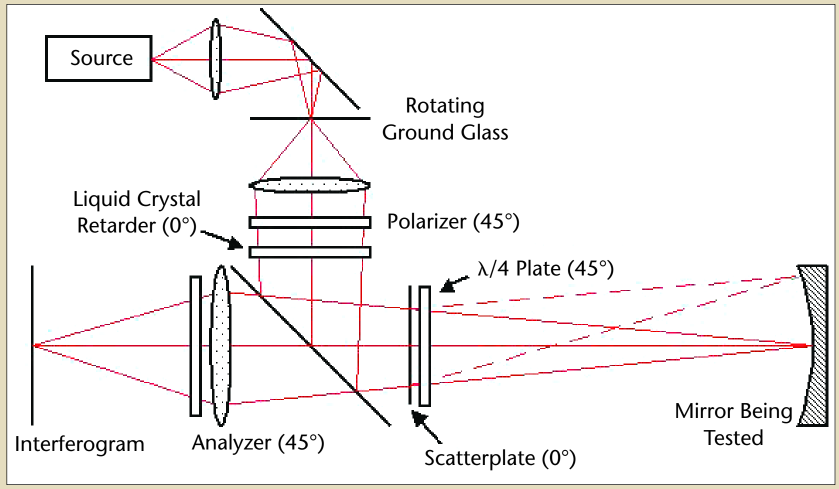



**Figure 3**. Phase-shifting scatterplate interferometer.

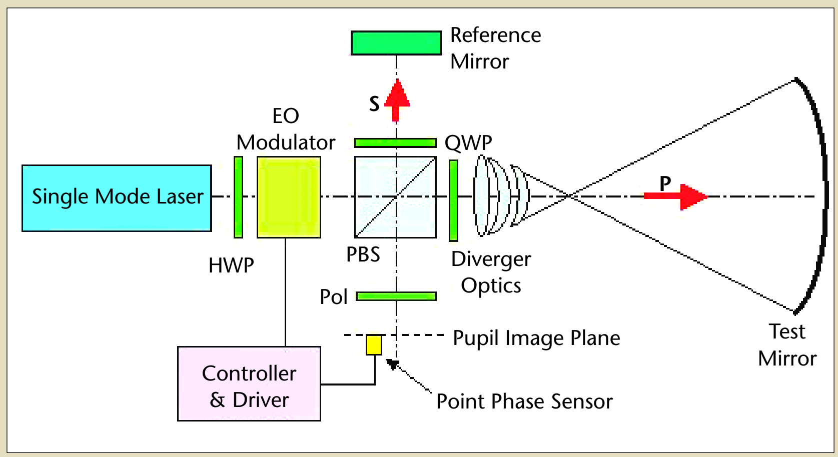



**Figure 4**. Closed-loop feedback vibration-compensated interferometer.

With a phase-shifting scatterplate interferometer, the goal is to control when the test and reference beams are scattered. The birefringent scatterplate shown in Fig. 2 provides the desired control. The appropriate aperiodic pattern with inversion symmetry required for a scatterplate interferometer is etched into a calcite retarder by use of a chemical etching process. Index-matching oil, chosen to match the ordinary index of the crystal, is then pressed between the calcite and a glass slide. The result is that for light polarized along the ordinary axis of the crystal, the index of the oil and the index of the crystal appear the same and the light passes directly through the scatterplate; the light polarized along the extraordinary axis of the crystal, on the other hand, sees an index difference and is scattered by the rough surface. This property controls whether the test beam or the reference beam is scattered.

A schematic diagram of the phase-shifting scatterplate interferometer is shown in Fig. 3. If the polarization

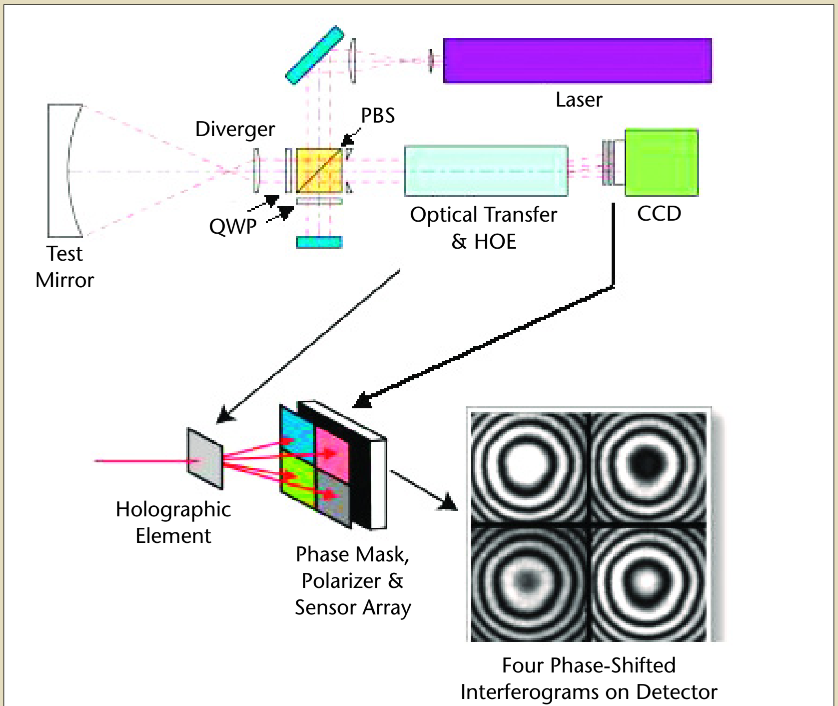



**Figure 5**. Single-shot interferometer (PhaseCam) showing beam divider and phase-shifting mask.

elements such as wave plates and polarizers are removed, it is a conventional scatterplate interferometer. The polarizer passes linearly polarized light oriented at 45° with respect to the optic axis of the calcite scatterplate, providing equal amplitudes for the component of the beam polarized along the optic axis and the component polarized orthogonal to the optic axis. The component parallel to the optic axis will see the extraordinary index of the crystal and the perpendicular component will see the ordinary index. A liquid crystal retarder produces a variable phase shift between the two orthogonal components of polarization. The scatterplate is located at the center of curvature of the test mirror and scatters only the component of the beam that is polarized parallel to the optic axis of the crystal. The perpendicular component passes through the scatterplate and forms an image of the source on the test mirror. Both the scattered and direct beams pass through a quarter-wave plate twice, producing a 90° rotation in the direction of polarization of each. As a result, on the second pass through the scatterplate, the beams change roles: the one that traveled directly through on the first pass is now scattered and the one that was scattered now passes directly through. The outcome is a scattered-direct and direct-scattered beam with orthogonal polarization. If an analyzer is placed in the beam, good quality interference fringes are obtained. If the interference fringes are phase shifted by applying a voltage to the liquid-crystal retarder, a reduced-vibration-sensitive phase-shifting interferometer is obtained.

## Closed-loop feedback vibration-compensated interferometer

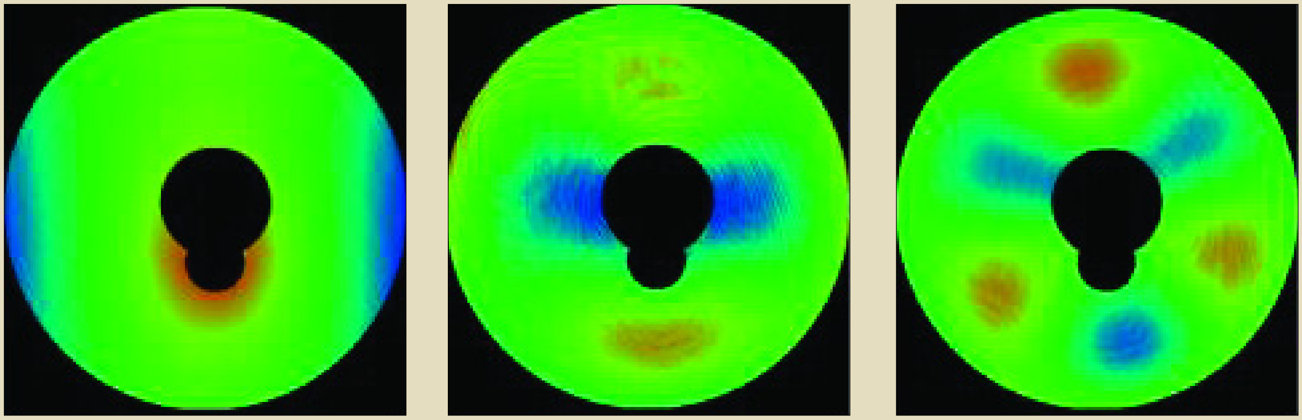
A second approach to reducing the effects of vibration is to sense the vibration and cancel it in the interferometer. This is the same concept used in modern noise-canceling audio headsets. The vibration of a rigid object generally produces a large piston term, smaller tilt terms and much smaller higher-order terms. In the absence of massive air turbulence, the piston term is usually the predominant factor. In a closed-loop feedback vibration-compensated interferometer, the vibration is sensed by use of a high-frequency single-point phase sensor and the phase of either the reference beam or the test beam phase is changed to compensate the effects of the vibration. This process is shown in Fig. 4, where the test and reference beams have orthogonal polarization and to cancel the effects of rigid body vibration, an electro-optic modulator is used to vary the phase difference between the two.

This approach works amazingly well for piston vibration that occurs within the bandwidth of the feedback loop, which might be 1 MHz or so. With the feedback system turned off, the fringe pattern may be moving so fast that it is invisible. Switching on the control loop instantly freezes the pattern, enabling very-high-quality phase measurement. The big limitation of this approach is that only low-order vibration can be handled, although vibration due to tilt could be handled with a separate tilt sensor and a second feedback loop. Likewise, only low-frequency air turbulence can be measured and reduced by data averaging. Another drawback of these systems is that they are complex and contain numerous optical and electronic components.

## Phase-shifting single-shot interferometer

A better technique for reducing the effects of vibration is to take all the phase-shifting frames at once. There are several different types of single-shot phase-shifting interferometers. In one type, an interferogram with numerous tilt fringes is taken. The exposure time for the interferogram is so short that the vibration is frozen. The interferogram is analyzed in one of two ways.

In the first approach, the interferogram intensity distribution is Fourier transformed and filtered and Fourier transformed again to obtain the wave front. For the first Fourier transform to be adequately filtered, a sufficient number of tilt fringes must be present. This technique works reasonably well, but because the filtering process smooths the



0.304 kHz 3.130 kHz 4.030 kHz

**Figure 6**. Disk vibrational modes.

wave front, the accuracy of the wave front near the edge of the pupil is limited.

A second approach that works with a single interferogram having many tilt fringes requires that the tilt be selected so that there are four detector elements between fringes. In this case, the phase of the tilted reference wave changes 90° between adjacent detector elements (360° between fringes). Phase-shifting algorithms can then be used to calculate the phase using the intensities measured by the four adjacent detectors. This technique works well if the test wave front has no aberrations, because then the fringes are equally spaced. If aberrations are present, however, the fringe spacing changes and the detector spacing is no longer exactly one quarter the fringe spacing. Often, this measurement technique does work sufficiently well because as the aberrations become larger, the accuracy to which the phase distribution must be measured is decreased. There are other single-shot interferometers that provide more accurate measurements; they are, however, more complex.

There are several techniques for simultaneously obtaining four phase-shifted interferograms. While so-called single-shot phase-shifting interferometers have been available for some time, they normally use four separate CCD cameras. Both the calibration and the alignment of the four cameras are critical and accuracy can suffer if both are not exact.

A superior approach is to have all four phase-shifted frames fall on a single CCD camera, as shown in Fig. 5. In this type of interferometer, a polarization beamsplitter causes the reference and test beams to have orthogonal polarization. Quarter-wave plates are placed in the reference and test beams so the beam transmitted the first time through the beamsplitter is reflected the second time, and vice versa. After the two orthogonally polarized beams are combined, they pass through a holographic element that splits them into four separate beams; this results in four interferograms. The four beams pass through a birefringent 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°. A polarizer with its transmission axis at 45° to the direction of the polarization of the test and reference beams is placed after the phase masks just before the CCD array. Thus, all four phase-shifted interferograms are detected in a single shot on a single detector array.

With short exposures the vibration, as well as the air turbulence, is frozen. The effects of air turbulence can be reduced by taking many sets of data, ensuring the time between the different data sets is long compared to the time it takes for the turbulence to change, and then averaging the data.

Not only can the effects of vibration be eliminated, by making short exposures to freeze the vibration, the vibrational modes can be measured. Figure 6 shows an example of measuring vibrational modes of a disk as a function of frequency. Movies showing the vibration can be made. Likewise, flow fields can be measured. Techniques such as the single-shot PhaseCam interferometer should greatly increase the number of applications in which interferometers for measuring dynamic systems can be used in less-than-ideal environments. The combination of modern electronics, computers and software with traditional interferometric techniques provides for very powerful measurement capabilities.

## Acknowledgments

The author acknowledges useful conversations with Michael B. North-Morris, James E. Millerd, Neal J. Brock and John Hayes.

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