Optical Methods in Experimental Mechanics

Part 46: Measuring Phase Difference—Part II: Compensation

REVIEW AND PURPOSE

The idea of using intensity measurements to determine the phase difference between interfering waves was introduced in the previous article. The two main pieces of data that must be obtained when performing such measurements were identified as: (1) the nearest whole interference order, and (2) the partial interference order beyond the nearest whole order. Some form of order counting meets the first requirement. The theoretical basis for using intensity observations along with the intensity-phase equation to meet the second requirement was developed.

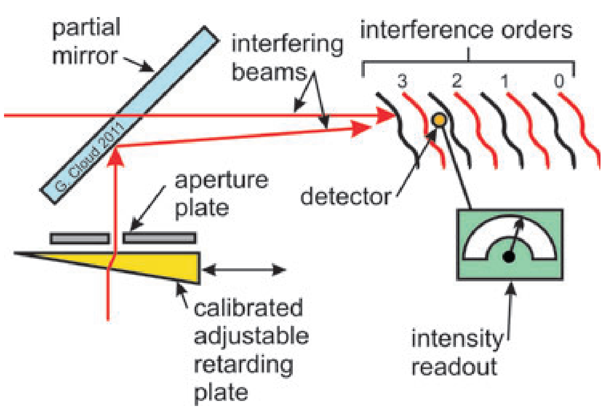
Before pursuing further the development of the general phase-shifting approach, it seems a good idea to spend a little time learning about the oldest technique for measuring partial interference order. There are three reasons for choosing this route, namely: (1) the method is very useful and worthy of study; (2) it suggests that photometric devices are useful in measuring phase change; (3) it establishes the concept of introducing into one of the interferometric paths a device that adds a known amount of path length difference (PLD) or phase change. Historically, the device is called a compensator; but, in contemporary parlance, it is a phase shifter.

Babinet-Soleil compensator manufactured by Karl Lambrecht Corp. of Chicago, Illinois, USA, and obtained by the author in ca. 1966. This device incorporates two crystal quartz wedges and a flat quartz plate mounted in a precision azimuth mount. At $\lambda = 633$ nm, the least Retardation reading is 0.0065λ, and range is 6λ. Photo by G. L. Cloud at Michigan State University, 2011.

This article introduces the use of a compensator or phase shifter along with a photometric device to accurately measure path length changes via interferometry.

THE COMPENSATION TECHNIQUE

The concept of the compensation technique is best learned through a thought experiment that aids in visualization. Consider the illustration below, which shows the business end of any type of interferometer where the two beams are brought together to create the oscillations of intensity commonly known as a fringe pattern.



The series, Optical Methods–Back to Basics, *is written by University Distinguished Professor Gary Cloud of Michigan State University in East Lansing, Michigan. It began by introducing the nature and description of light and will evolve, with each issue, into topics ranging from diffraction through phase shifting interferometries. The intent is to keep the series educationally focused by coupling text with illustrative photos and diagrams that can be used by practitioners in the classroom, as well as in industry. Unless otherwise noted, the graphics in this series were created by the author.*

The series author, Professor Gary Cloud (SEM Fellow), is internationally known for his work in optical measurement methods and for his book, Optical Methods of Engineering Analysis.

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The axes of only two interfering waves are shown, but likely two broad beams or wave bundles are caused to interfere. Two factors affect the fringe pattern. First, the beams are likely not exactly collinear, so oblique interference (see Part 4 of this series) creates a standing wave fringe pattern in space. The phases of the component waves might vary smoothly across one or both of the beams, which causes undulation of the fringes. The result of the interference will be, as we have learned, a volume of interference fringes wherein the local intensity depends on beam intensities as well as the angle between the waves and the cosine of the local phase difference between the waves. In the sketch, the bright lines represent intensity maxima or whole-order fringes. The black lines are the intensity minima or half-order fringes. If a screen or a sensor array were placed in the area where the interference takes place, it would register a fringe pattern that is a cross-section of the fringes depicted.

An interferometer creates a volume of fringes in space. The objective is to measure exactly the interference order at a specific point in the field.

The experiment requires that the exact phase difference or fringe order be determined at a specific point in the field. Simple interpolation between fringes is not good enough. So, an intensity detector is placed at the desired location, as suggested in the sketch. The detector is sensitive to small changes of irradiance, but it need not be calibrated.

Whole- and half-order counting: Suppose for temporary convenience that the experiment was set up so that the initial phase difference between the beams impinging on the detector was zero, meaning that the starting detector output is maximum. Further, suppose that the phase difference between the beams increases as the experiment progresses. The fringes would seem to move left or right while maybe retaining their shape. This behavior is suggested in the sketch by showing the progression of fringe orders in space. As the fringes move past the detector, its output oscillates between maxima and minima. By counting these oscillations, we are able to determine the nearest whole fringe order that has passed as the final stage of the experiment is reached. The illustration shows that two bright fringes have passed, and, in fact, the next half order has also passed, so the path length difference between the interfering beams must be between 2.5 and 3 times the wavelength of light (λ) at the location of the detector.

As path length difference changes, the fringes appear to move past the detector.

To determine nearest whole- and half-orders, count the cycles of maximum and minimum detector readings as the experiment progresses from its initial state to its final state.

Measuring fractional interference order: The next step is to measure the exact partial fringe order at the detector location in order to gain precision. To accomplish this task, we insert into one of the beams a calibrated graduated retarding device, otherwise known as a phase shifter or a compensator. The function of this tool is to introduce a known path length change into that beam. The sketch above suggests that the compensator can be a transparent wedge of refracting material, and, in fact, such a simple solution can be made to work. Whatever the construction of the compensator, it must be carefully calibrated to relate its position to the phase change it causes for the specific wavelength of light being used.

To measure exact partial interference order, insert into one of the interferometer paths a graduated calibrated adjustable retarding plate, which is called a phase shifter or a compensator.

The compensator is adjusted so as to cause the detector output to reach a maximum. This means, conceptually, that the second-order fringe has been advanced to the detector location; or, alternatively, the third-order has been backed up to that spot. Which is it? This question is critical, and the answer is not all that simple. One tidy approach is to observe whether the detector output decreases before increasing again. If so, then the added path length must have been greater than half the wavelength. For this thought experiment, we already know that the fringe order is greater than 2.5, so we must have advanced the second order to the detector location. Suppose that the compensator scale reads 0.712. At last, we know that the exact path length difference is 2.712λ. Further, if the detector output did not pass through a minimum before reaching the maximum, then the third order fringe had been backed up to the detector location. The compensator would read 0.288, and the exact fringe order would be $3.000 - 0.288 = 2.712$, the same as before. Good practice is to work the technique both ways in order to check the result.

Adjust the phase shifter so as to bring the detector output to a maximum, which is equivalent to moving the next lower or next higher whole order to the detector location. The phase shifter, if properly calibrated for the wavelength used, reads out the fractional fringe order.

- *Care is required to determine if the reading should be subtracted from the higher order or added to the lower order.*

If the starting intensity is not a maximum, as was assumed, then the initial interference order is measured as outlined above, with the nearest whole order arbitrarily numbered. Keep track of the passage of whole orders and measure the final partial order. Subtract the starting order from the final value to obtain the change of path length during the experiment. Likewise, you might have to take the initial value of the phase shifter setting into account.

If the starting intensity is not a maximum, then the initial interference order is measured using the same procedure, with the nearest whole order arbitrarily numbered. The initial measurement is then subtracted from the final measurement.

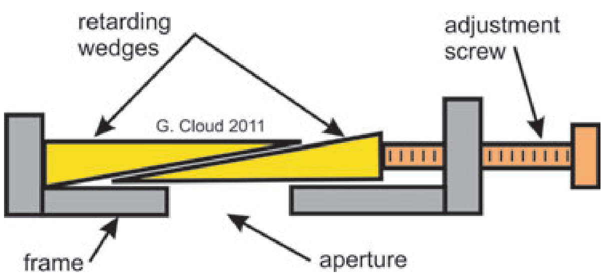
COMPENSATORS

Many types of compensators and phase shifters have been fabricated and used in interferometric experiments. Some you can make yourself, but they are usually purchased along with calibration specifications from vendors who specialize in precision optical apparatus. Only a few implementations can be mentioned here. The simplest, as suggested in the illustration above, is a slender wedge or stepped plate of glass or quartz. The main problem with the wedge design is that it causes lateral deviation of the wave. Also, it creates a variance of path length change across the field, so an aperture is used in order that the experimenter can know which area of the compensator is affecting the waves that reach the detector.

These problems are eliminated by using superimposed wedges as shown conceptually in the sketch below.

Many types of phase shifters have been invented and used, including:

- *a glass or quartz wedge with an aperture,*
- *two glass or quartz wedges in contact, but with one able to slide over the other so as to create a slab whose thickness can be changed,*
- *a mirror fastened to a piezoelectric crystal that is controlled by a driving voltage,*
- *rotation of one of the polarizers in photoelasticity,*
- *for photoelasticity, a calibrated tensile specimen of birefringent material.*



This device is essentially a variable-thickness plate of quartz or glass, so it produces a uniform path length change over its entire window. Some mechanism must be provided to keep the wedges in tight contact while allowing one to slide relative to the other.

For photoelasticity experiments, compensation can be performed by merely rotating one of the polarizers, a class of methods called goniometric compensation (Tardy and Senarmont methods). Alternatively, you can introduce a separate compensator that might be as simple as a calibrated tension specimen of birefringent material (the Coker compensator), or a device containing two quartz wedges in the arrangement shown above (the Babinet-Soleil compensator), an exemplar of which appears in the photo at the head of this article.

Nowadays, phase shifting is usually accomplished by attaching a front-surface mirror to a piezoelectric crystal. The mirror is inserted into one leg of the interferometer in place of the usual fixed mirror. The crystal, when excited by a driving voltage, causes the mirror to move through known fractions of the wavelength, thereby introducing the required path length change.

Accurate calibration of the phase shifting device can be accomplished through interferometry conducted as outlined above or by comparison with a standard.

IMPROVING SENSITIVITY

As mentioned in Part 45 of this series, it is difficult to determine from the detector output exactly when maximum or minimum intensities are reached. The reason is that the slope of the cosine curve is zero at its peaks. Relatively large changes of induced path length yield only small changes of output in these regions. Improved sensitivity can be gained by measuring intensities where the slope of the intensity-phase curve is greatest, that being at the midpoint of the swing from light to dark. Take measurements at approximately this output level symmetrically placed on either side of the maximum or minimum and average them to obtain the compensator setting that corresponds to the true peak value. This procedure assumes that the phase-intensity relationship is symmetrical, which is probably true in the local sense.

Sensitivity can be enhanced by detecting intensities that are at the midpoint of the swing from maximum to minimum. Two compensator readings are taken at this level, one on either side of the whole- or half-order. These readings are averaged to give the correct value.

WHAT IS NEXT?

The single-detector compensation technique described above is capable of great accuracy, but it is tiresome if many measurements are to be taken. Imagine the improvement if an array of detectors were used and their outputs were somehow processed in parallel to obtain a whole-field map of phase change.

The next articles will extend the experiment described above to explain how phase difference can be obtained directly through use of the phase-intensity relationships and an intensity detector. ■

The next articles will explain how phase difference can be obtained directly through use of the phase-intensity relationships and an intensity detector, a process that can be automated and extended to yield a phase map over the entire field.