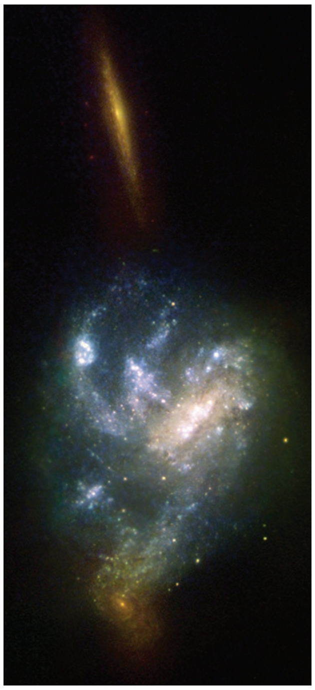
OPTICAL METHODS Back to Basics *by Gary Cloud*

Optical Methods in Experimental Mechanics
Part 17: Laser Doppler Interferometry



An example of the optical Doppler frequency shift is provided by this photo of galaxy NGC 7673 in the constellation Pegasus. Two other galaxies are seen in the background. These galaxies are further away and are receding faster, so they appear reddish owing to their greater Doppler red-shift. Photo from Hubble Wide Field Planetary camera. Courtesy of European Space Agency and Nicole Homeier of the European Southern Observatory and University of Wisconsin-Madison.

REVIEW AND PURPOSE

The previous article in this series described the Doppler effect, which causes the frequency of radiation emitted from a moving source or received by a moving observer to be different from that seen if no motions take place. This Doppler frequency shift was calculated in terms of the velocity of a moving source. It seems that the Doppler shift can be used to determine the velocity of an object if it can be measured.

Two related objectives are undertaken here. The first is to describe how interferometry is used to measure the Doppler shift. The second is to properly understand the frequency shift for the case where light is reflected from a moving object instead of being emitted from the object. Some application examples are then given.

Objectives are to:
- *learn how to measure Doppler shift using interferometry,*
- *calculate the frequency shift for light that is reflected from a moving target,*
- *explore some useful applications of Doppler interferometry.*

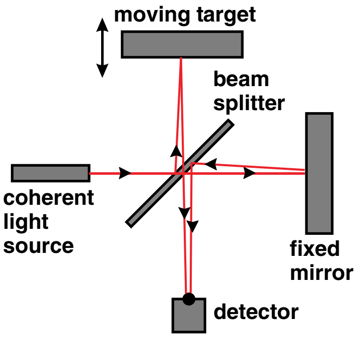
Measurement of Doppler Frequency Shift

Determination of the Doppler frequency shift by measurement of the original and shifted frequencies and then subtracting the one from the other is not appropriate unless the velocities and resulting frequency shifts are very large, as might be the case for certain astronomical observations. For the speeds involved in typical engineering applications, the problem is poorly conditioned in that the small change in a large quantity is sought, so the potential error is large.

Measurement of the Doppler frequency shift for typical velocities involves the determination of the small change in a large quantity.

As is usual and wise in this situation, the measurement is instead performed in differential or comparison mode. Interferometry offers a natural approach to the direct determination of the Doppler shift.

Several interferometric schemes satisfy the need. For this discussion, consider the Michelson arrangement (see Part 8 of this series) shown in the sketch below.



Interferometry is a simple and accurate way to measure the small Doppler frequency shift for optical applications in engineering.

Editor's Note: Optical Methods: Back to Basics, *is organized by ET Senior Technical Editor, Kristin Zimmerman, General Motors, and written by Prof. Gary Cloud of Michigan State University in East Lansing, MI. The series 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 noted otherwise, graphics in this series were created by the author.*

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

If you have any comments or questions about this series, please contact Kristin Zimmerman, Kristin.b.Zimmerman@gm.com.

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OPTICAL METHODS IN EXPERIMENTAL MECHANICS

Rather than a broad collimated beam, only a single wave train or small pencil of light, as from a laser, is used to interrogate the moving target, which carries a reflective or scattering surface that bounces some of the incident radiation back to the photodetector. The target motion causes a shift in the frequency of that radiation. The mirror in the second interferometer arm is shown as fixed, although it can also be moving if the difference between two target velocities is sought. The two light-wave trains, which combine interferometrically at the detector, have different frequencies ν and ν', as was shown in Part 16 of this series.

The Michelson interferometer:
- is an excellent classical approach for measuring Doppler shift,
- provides a paradigm for understanding measurements of this type,
- interferometrically combines a portion of the original wave from the source with the wave reflected or scattered from the moving target.

The electric vector for the sum of these waves at the detector is,

$$E_S = A_1 \cos(2\pi\nu t + \phi_1) + A_2 \cos(2\pi\nu' t + \phi_2) \qquad 17.1$$

The irradiance will be,

$$\begin{aligned} I &= |E_S|^2 \\ &= A_1^2 \cos^2(2\pi\nu t + \phi_1) + A_2^2 \cos^2(2\pi\nu' t + \phi_2) \\ &\quad + 2A_1A_2 \cos(2\pi\nu t + \phi_1)\cos(2\pi\nu' t + \phi_2) \qquad 17.2 \end{aligned}$$

Use the identity for the product of two cosine functions to convert the irradiance to the following form, where $\phi = \phi_1 - \phi_2 =$ the phase difference.

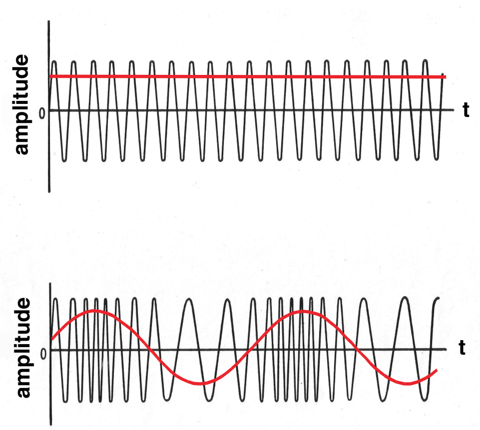
$$\begin{aligned} I &= A_1^2 \cos^2(2\pi\nu t + \phi_1) + A_2^2 \cos^2(2\pi\nu' t + \phi_2) \\ &\quad + A_1A_2 \cos[2\pi(\nu' + \nu)t + \phi] + A_1A_2 \cos[2\pi(\nu' - \nu)t + \phi] \qquad 17.3 \end{aligned}$$

The first three expressions in the irradiance result describe waves that oscillate at frequencies equal to, slightly less than, or greater than the basic radiation frequency for object velocities in the range considered here. If light waves are being used, then these frequencies are too large to be tracked, so only a time-average value, essentially a constant, would be displayed by the detector for these three waves.

Combination of the original beam with the Doppler-shifted beam yields:
- *3 waves of such high frequency that they cannot be tracked by a detector and so are not useful,*
- *1 wave that oscillates at the beat frequency and so can be tracked by a detector to yield the Doppler shift.*

The final expression in the irradiance is the one of interest. It describes an output that is proportional to the cosine of the difference between the original frequency and the new Doppler-shifted frequency. In other words, it is an irradiance oscillation at what is usually thought of as the "beat frequency." This difference frequency will be low enough so that it can be tracked by ordinary photodetectors.

As an elementary example, suppose that the target has a constant velocity and its motion is analyzed with the Michelson interferometer. The output from the detector will be a harmonic wave of constant frequency as suggested in the upper panel of the following sketch. The red line is the target speed, and the black trace is the detector output.



The output of the Doppler interferometer is a frequency-modulated wave whose instantaneous frequency is proportional to the speed of the target.

That the ***frequency*** of the output signal is the indicator of target velocity should not be forgotten, because our habit is to think of the amplitude of the output as the important data. To underline this idea, suppose that the target is vibrating instead of moving at constant speed. The detector output will then be a frequency-modulated wave of the sort shown in the lower panel of the sketch. As before, the red line is the target velocity as a function of time. The black trace is the frequency-modulated signal from the detector on the same time scale. At any instant, the frequency is proportional to the instantaneous velocity of the target. For the example shown, a bias frequency has been incorporated for reasons mentioned below, and it must be taken into account in interpreting the signal.

THE MOVING FRINGE APPROACH

An alternative approach to understanding the Michelson interferometer and its use in measuring velocities by the Doppler method is to calculate the rate at which interference fringes cross the detector. Think of one of the mirrors as being tilted slightly so that a system of parallel interference fringes is created near the detector by oblique interference (see Part 4 of this series). If, now, one of the mirrors is given a velocity, a time-varying path length change is introduced, which causes the interference fringes to move across the detector to create an irradiance variation. Phase shift calculations give a result that is the same as that presented above. This mathematical development is not pursued here.

An alternative approach to interpreting the Doppler interferometer is to calculate the rate at which oblique interference fringes move across the detector when the target object moves.

BIAS FREQUENCY

A problem with the basic Doppler technique described so far is that the sign of the target velocity is not easily distinguished. This difficulty and artifacts derived from the processing of low-frequency signals are eliminated by introducing a bias frequency signal, which, in this case, functions as an Frequency Modulation (FM) carrier wave, as suggested in the example discussed above.

The bias frequency is created by introducing into one arm of the interferometer a frequency-shifting device. A constant velocity of the reference mirror accomplishes this aim, but it cannot go on for long. Oscillation of the reference mirror can be used, but it introduces a frequency modulation itself. One practical method is to introduce into the optical path a diffraction grating that is rotated at constant speed. The angular deviation of the diffraction grating coupled with its rotation creates a constant Doppler shift in the reference arm. A better approach is to use an electro-optic device such as a Bragg cell to create the bias frequency deviation.

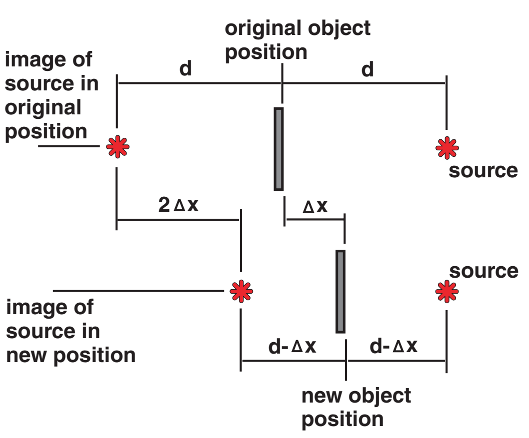
Introduction of a bias frequency shift:
- *facilitates determination of the sign of target motion,*
- *eliminates some data processing artifacts,*
- *creates a frequency-modulated carrier wave,*
- *is implemented by introducing into the interferometer, for example:*
  - *motion of the reference mirror,*
  - *a rotating diffraction grating,*
  - *a Bragg cell.*

DOPPLER SHIFT FOR REFLECTED LIGHT

Most engineering applications of Doppler motion measurement involve interrogation of the target object with a light beam that is reflected or scattered back to the detector, as suggested by the Michelson model discussed above. We expect that the apparent source velocity as indicated by the Doppler shift and our equations will be different from the actual target velocity, because the light traverses the object arm of the interferometer twice and a reflection is involved.

The Doppler shift for a moving source differs from that observed when the light is reflected or scattered from a moving target.

The figure below guides our thinking about this problem.



In the upper part of the figure, the reflective target is at a distance d from the source. The laws of reflection prescribe that the image of the source will be at the same distance behind the target. In the lower part of the figure, the target has moved forward by amount Δx so that it now lies a distance $d - \Delta x$ from the source. As before, the image of the target is now at this same distance from the target. The image of the target has moved forward a distance $2\Delta x$, or twice the target motion. Differentiation with respect to time demonstrates that the velocity of the image is twice the velocity of the target. For this reflection case, then, the Doppler shift indicated by the interferometer is twice what it would be for a simple moving source.

Consideration of the laws of reflection shows that the Doppler frequency shift for light reflected from a moving target is twice that for light from a moving source.

APPLICATION EXAMPLES

Doppler interferometry is widely used in engineering to measure the motions, vibrations, and mode shapes of structures and machine components as well as fluid flow fields by what is usually called Laser Doppler Vibrometry or Laser Doppler Velocimetry (both LDV). Powerful scanning or imaging laser Doppler interferometry systems, called Doppler Picture Velocimetry (DPV), yield a full-field picture of the specimen velocity field. Laser Doppler methods are so sensitive and accurate that they have become techniques of choice for the calibration of other motion measurement devices such as accelerometers.

Sample useful applications of optical Doppler interferometry include:
- *Laser Doppler Velocimetry (LDV), as used in fluid flow studies,*
- *Laser Doppler Vibrometry (LDV) as used in vibration and modal analysis,*
- *calibration of other motion measuring devices such as accelerometers,*
- *the laser gyroscope.*

Doppler interferometry is also fundamental to the function of the laser gyroscope that senses rotations and that has no moving parts. Mirrors or fiber optics are used to direct light waves in opposite directions around a ring or a triangular path to converge at a detector. If the ring is stationary, no frequency shifts are created, so no beat frequency is observed. If the device rotates, the frequencies of the two beams will undergo equal and opposite Doppler shifts. The beams are mixed at the detector to produce an oscillating signal whose frequency is proportional to the rotational speed of the gyroscope.

While not interferometric in function, applications of the Doppler effect in such fields as medical diagnosis, for example in measuring blood flow rates inside the body, should not go unnoticed. These techniques have saved the lives of many of us.

A LOOK AHEAD

The next few articles in this series will deal with geometric moire in its various manifestations. ■

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