OPTICAL METHODS Back to Basics *by Gary Cloud*

Optical Methods in Experimental Mechanics
Part 16: The Optical Doppler Effect

REVIEW AND PURPOSE

The interferometric processes studied so far in this series have primarily utilized light to measure optical path length differences or changes of optical path length. The path length changes of interest are caused either by changes in the physical path or else by variations of wave speed resulting from changes of index of refraction.

The Doppler technique differs in that velocities of objects are measured through interferometric observation of changes of optical frequency. Path length data are not relevant. The output, whether viewed as a frequency-modulated intensity or as moving interference fringes, indicates the shift in the frequency of radiation that is emitted by a moving source, received by a moving observer, or reflected from a moving test specimen. Laser Doppler interferometry, often called laser Doppler velocimetry (LDV), is widely used in investigating the dynamic behaviors of solid materials, fluids, and structures; and sophisticated instruments that utilize this principle are readily available. In common with most optical techniques, it is remote and noncontacting, and only optical access to the specimen is needed. Its sensitivity and dynamic range are remarkable.

Our task is to relate the Doppler frequency shift to object motion. Later, we will discover how the frequency shift can be observed and interpreted.

THE DOPPLER EFFECT

The acoustic Doppler shift is familiar to anyone who has noticed the change in pitch of the whistle of a train that is passing on a nearby track. The phenomenon is used to good effect by handbell ringers when they swing a rung bell to create a slow vibrato in an otherwise static pitch. It is easy to distinguish between the sound of a steeple bell that swings against its clapper and the sound of a stationary carillon bell that is struck. What we hear is the increase or decrease of the frequencies of the emitted waves depending on whether the vibrating source is moving toward or away from us.

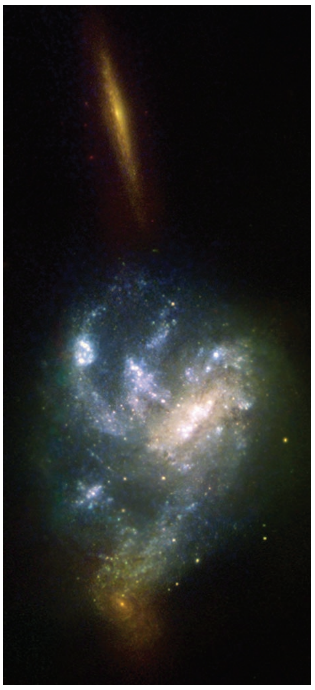
Reliance on the acoustic model to explain the optical manifestation of the Doppler effect is troublesome if carried to extreme. Some clarifications of history and the differences between acoustic and optical Doppler shifts deserve brief mention.

The Austrian scientist Christian Johann Doppler (1803–1853) explained how the velocity of the source affects the perceived frequency of sound waves. He also theorized that because the pitch of sound from a moving source varies according to source speed, then the color of light from a star should vary according to the star's velocity relative to earth. The French physicist Armand-Hippolyte-Louis Fizeau (1819–1896) later clarified the theory of the Doppler effect in starlight and demonstrated how it could be used to measure relative velocities of stars. In

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.



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.

Laser Doppler interferometry:
- *measures the velocities of objects,*
- *uses interferometric observation of the change of frequency of light that is:*
  - *emitted by a moving source*
  - *recorded by a moving observer*
  - *reflected from a moving object*
  - *some combination of the above*
- *is utilized in determining dynamic behavior of materials and structures.*

The objective is to relate the Doppler frequency shift to the relative velocity of source and observer.

The acoustic Doppler frequency shift that is caused by a moving sound source:
- *provides a good example of the Doppler effect,*
- *is easy to detect aurally, as when listening to a train pass on a nearby track or hearing a moving bell.*

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the context of astronomy and applied optics, the phenomenon is often called the Doppler-Fizeau effect.

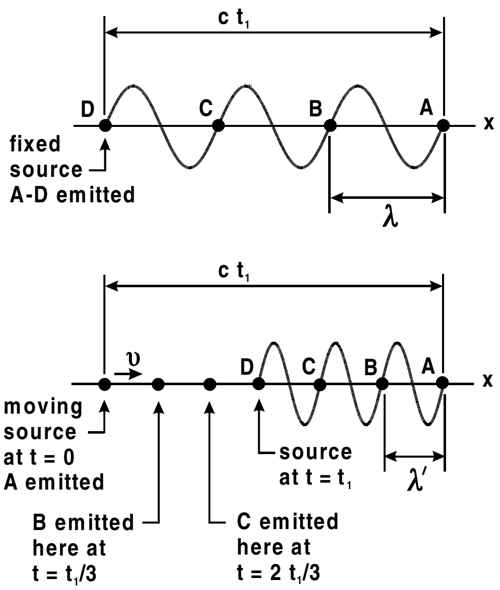
For most waves, including sound, the observed wave velocity differs depending on the velocity of the observer. The notable exceptions are electromagnetic waves, including light, for which the speed of the wave is constant irrespective of observer speed. This means that the Doppler frequency shift for sound waves differs from the shift for light waves for any case where the observer is moving.

In particular, for light waves, the frequency recorded by a moving observer who intercepts waves from a fixed source differs from the frequency received by a fixed observer from a moving source, even if the relative velocities are the same. The reason for this apparent paradox is found in the theory of relativity and derives from the facts that the speed of light is invariant and that the clocks for moving and stationary observers are different. The calculation for the moving observer is not particularly difficult, but it will not be pursued here. The difference between predictions for moving source and moving observer is not measurable for speeds that are well below the speed of light, so it is not significant in most terrestrial applications.

Optical Doppler differs from acoustic Doppler effects in that:
- *the perceived speed of light waves does not depend on the speed of the observer,*
- *the frequency shift for a moving observer differs from that for a moving source.*
- *However, the difference is not significant for ordinary terrestrial observations.*
- *The explanation for the difference lies in the Theory of Relativity.*

THEORY OF THE DOPPLER FREQUENCY SHIFT

Before learning how to utilize the Doppler effect, the relations between frequency shift and velocity must be understood. Two space diagrams that illustrate the mechanics appear below.



In the upper diagram, the source is at rest, and it emits a harmonic wave of wavelength λ that travels at speed c. At time $t = 0$, wave point A is emitted by the source. After an interval t_1, wave point A has traveled the distance ct_1, and wave point D is just then being emitted at the source. For this pictorial example, only three wave cycles, identified by wave points A–D, are emitted at equal intervals during the time t_1 to fill the space between A and D. In general, if n cycles are emitted during some interval t_1, then the space diagram suggests that,

$$n\lambda = ct_1 \qquad 16.1$$

Use the relationship $\nu = c/\lambda$ between wave speed c, frequency ν, and wavelength λ that was mentioned in part 10 of this series to obtain,

$$n = \frac{ct_1}{\lambda} = \nu t_1 \qquad 16.2$$

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The lower space diagram illustrates the situation if the source is moving to the right with constant speed υ, but with all other conditions remaining unchanged. Wave point A still leaves the source at time $t = 0$. Since the wave speed is invariant, it travels the same distance as before in time t_1. The second wave point B is emitted downstream at time $t = t_1/3$, wave point C leaves the source at time $t = 2t_1/3$, and wave point D will only just be emitted at the source location at time $t = t_1$.

Space-time considerations show that if the source is moving, the wavelength of the emitted radiation will be shortened or lengthened, depending on the direction of the motion with respect to the observer. Hence, the frequency will be increased or decreased.

Clearly, all three wave cycles must fit within the now-shorter space between the end point A and the final position D of the source. The source seems to have "caught up" to the waves it has previously emitted. So, the wavelength must be changed to some new value λ', and a fixed observer senses a new frequency ν'. In general, if n wave cycles are emitted by the moving source during the interval t_1, the new wavelength is calculated as follows,

$$n\lambda' = ct_1 - \upsilon t_1 \qquad 16.3$$

which yields for the value n,

$$n = \frac{(c - \upsilon)t_1}{\lambda'} = \left(\frac{\nu'}{c}\right)(c - \upsilon)t_1 = \nu'\left(1 - \frac{\upsilon}{c}\right)t_1 \qquad 16.4$$

The number of wave cycles emitted during a given interval is the same whether or not the source is moving, so results from equations 16.2 and 16.4 are equated to obtain the new frequency,

$$\nu' = \frac{\nu}{1 - \frac{\upsilon}{c}} \qquad 16.5$$

Note that a specific location for the observer need not be declared; we simply take a snapshot of the space that the source is moving into. This result is the new frequency ν' that would be seen when the source is moving toward the observer with velocity υ. In this case $\nu' > \nu$. Repetition of the calculation for the case where the source is moving away from the observer, using a snapshot of the space that the source is moving out of, shows that the new frequency is less than the original frequency, with the result,

$$\nu' = \frac{\nu}{1 + \frac{\upsilon}{c}} \qquad 16.6$$

The difference between the old and new frequencies $\Delta\nu = \nu - \nu'$ is the Doppler frequency shift. More is to be said about the sign of this quantity.

The results suggest that observation of the shift of frequency from a moving source can be used to determine the velocity of the source.

Clearly, if the speed of light and the original frequency of the radiation are known, and if the new frequency can be ascertained, then the speed of the source can be calculated. In the acoustic domain these quantities are quite apparent to us. However, optical frequencies are on the order of 10^{14} Hz; so, if the source velocities are not great, then the Doppler shift is relatively small. One faces the difficult problem of measuring the small change in a large quantity.

The Doppler shift in frequency is small relative to the large fundamental optical frequency for velocities encountered in typical engineering applications, so direct measurement of the change of frequency by measuring the original and final frequencies gives uncertain results.

As is usual in such an experimental situation, the measurement is performed in differential or comparison mode. The difference between the original frequency and the new frequency is measured directly through optical interferometry.

A differential measurement of the Doppler shift, wherein the frequency change is determined directly, is required.

WHAT'S NEXT?

The next article in this series will describe how interferometry is used to determine the Doppler shift. In experimental mechanics applications, the laser Doppler method usually employs radiation that is reflected or scattered from a moving target, so it is not actually a moving source. This situation will be examined so that the results of Doppler measurements can be properly interpreted. Finally, some examples of applications will be described in brief. ■

Interferometric comparison of the original light frequency with the changed light frequency allows accurate determination of the Doppler shift.

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