

A Century of Acousto-Optics: From Early Discoveries to Modern Sensing of Sound with Light

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Introduction

Acousto-optic sensing refers to the measurement of acoustic phenomena using *light*. The interaction between *sound* and *light* enables us to visualize and measure a wide range of acoustic phenomena that are difficult to observe with the most common type of acoustic sensors, the microphone. Such phenomena include, for example, the sound generated by a fast-moving source (e.g., a high-speed train), the three-dimensional (3D) sound field over a large volume (e.g., the reverberant field inside a room), or the interrelationship between acoustics and fluid dynamics (e.g., the combined sound field and airflow in front of a whistle).

Because no physical devices, such as conventional microphones and transducers, are introduced in the measured area, this type of measurement is remote and *noninvasive*. Such noninvasive measurements are relevant for a broad range of fields within acoustics, including metrology, underwater acoustics, architectural acoustics, bioacoustics, noise control, education, and generally all areas where the visualization and measurement of acoustic fields are of interest.

Still, acousto-optic sensing is relatively unknown to many acousticians; presumably, the application of these techniques has been limited by the lack of suitable technology and instrumentation. At present, however, we are witnessing substantial advances in optical technologies that are unlocking a vast domain of opportunity in the field. In this article, we describe the basics of acousto-optic sensing, summarize the historical development of optical methods to observe sound, and give an account on the-state-of-the-art through a few selected examples and current applications. We finalize with an outlook, looking ahead into some of the exciting prospects in the field.

The Acousto-Optic Interaction

In a transparent homogeneous medium, light rays travel uniformly and follow a straight path. However, media like air or water are rarely perfectly homogeneous; the propagation of light is affected by disturbances such as flow, turbulence, heat transfer, density changes, and sound waves. Therefore, light propagating through a given medium contains information about the inhomogeneity of that medium. Researchers in optics have been utilizing this effect for visualizing invisible phenomena. Changes in the propagation of light caused by inhomogeneities are described by the *refractive index* (Feynman et al., 1964), a quantity that represents the *slowness* of light propagation.

As acousticians, what we are interested in the most is how the presence of sound waves modifies the propagation of light, a phenomenon called *acousto-optic interaction*. In this article, we focus on the frequency range from 20 Hz to 20 kHz (i.e., the audible range for humans) propagating in air at “normal” sound levels (e.g., below 130 dB re 20 μ Pa).

The different ways in which light and sound interact are illustrated in **Figures 1** and **2**. Acousto-optic effects can be classified into three phenomena: diffraction, refraction, and retardation.

A laser beam traveling across a high-frequency sound wave experiences *diffraction* (**Figure 1a**). The laser beam gets diffracted into several beams, with directions that depend on the acoustic (sound) and electromagnetic (laser) frequencies. Acousto-optic diffraction occurs when the width of the laser beam is larger than the acoustic wavelength (i.e., when the laser beam is “thicker” than the distance between the wave crests). In this case,

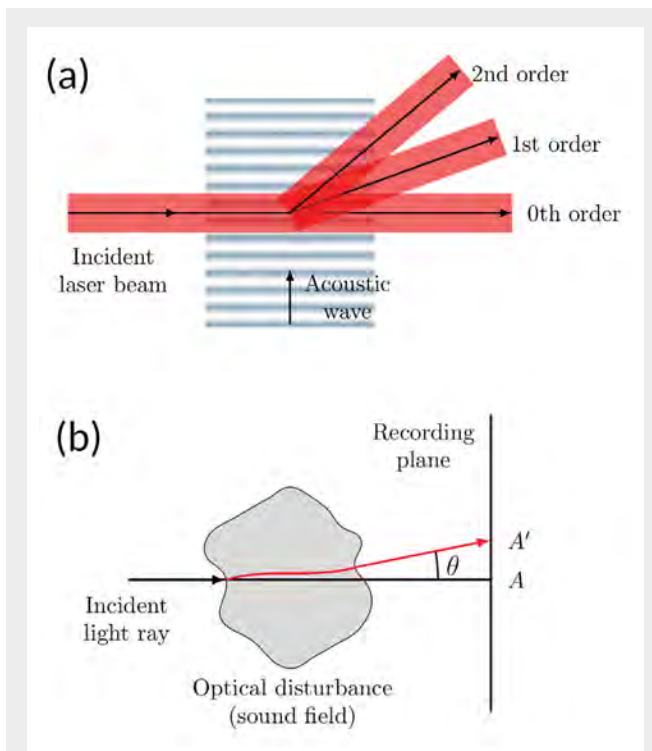


Figure 1. Two types of interaction between acoustic waves and light. **a:** Diffraction of a laser beam by ultrasonic waves. **b:** Refraction of a light ray by an optical disturbance. See text for explanation.

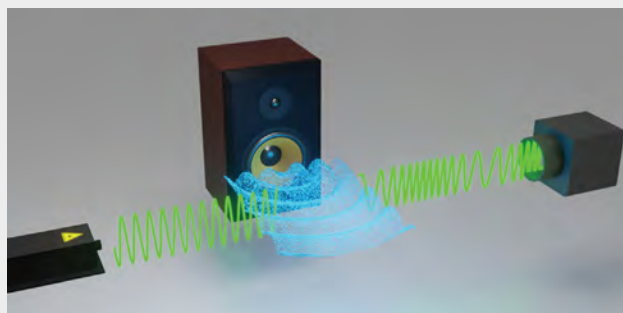


Figure 2. Acousto-optic sensing of sound based on changes in the phase of the electromagnetic wave (light) due to acoustic waves. The electromagnetic wave (**green**) traveling through a sound field (**blue**) experiences a phase shift. The change is detected by optical means (e.g., a high-speed camera).

the acoustic wave causes the light beam to diffract as if it was passing through a grating. The acousto-optic diffraction is the underlying principle of many devices

used in modern laser technology to modulate light and generate ultrafast laser pulses.

Light rays traveling through a sound field also experience *refraction* (**Figure 1b**) when the sound field produces gradual variations of the medium's refractive index on the laser path. As shown by Fermat's principle, when light travels between two points, it will always take the path that requires the shortest time (formally, the path of minimum *optical path length*, defined as the integral of the refractive index over the geometrical path). Therefore, light rays *refract* or *bend* toward regions of smaller refractive indices.

Two classical visualization techniques based on the refraction of light are *shadowgraphy* and *schlieren*. Shadowgraphy consists of recording the displacement of the light rays (distance $A-A'$ in **Figure 1b**). In schlieren, an optical image of the angular deflection (θ in **Figure 1b**), is formed (Settles, 2001).

In addition to diffraction and refraction, light also experiences apparent *retardation* or a *phase shift* when traversing a sound field (**Figure 2**). Monochromatic light can be described as an electromagnetic wave, with a frequency, amplitude, phase, and polarization. Acoustically induced changes in the refractive index change the apparent velocity at which light propagates, as if light would travel slightly slower in areas of high pressure and slightly faster in areas of low pressure (Torrás-Rosell et al., 2012). These changes translate into a phase shift of the electromagnetic wave, which can be measured via *interferometry* (interferometry refers to the superposition of two light beams, one that is exposed to the sound wave and one that is undisturbed and acts as a reference).

Of the three phenomena, refraction and phase shift have been used for visualizing audible sound fields. The refraction caused by acoustic waves is so small that very high sound pressure levels are typically required to record shadowgrams and schlieren images of sound waves. Although the phase shifts induced by acoustic waves are also small, optical interferometers are very precise and they can capture such phase shifts. Interferometry is often used in today's state-of-the-art methods for measuring audible sound. Some of them are presented in **Acousto-Optic Sensing Today**.

Historical Background of Acousto-Optic Sensing

First Visualizations

The visualization of sound fields is a powerful means to understand how sound propagates. Early records dating as far back as classical Greece and Rome (Kilgour, 1963) contain analogies between water waves and sound fields to build an intuitive understanding of how sound “fills a space.” It was not, however, until the nineteenth century that specific techniques to visualize audible sound and other invisible phenomena were developed. The underlying principle of these visualization methods is the refraction of the light rays caused by changes in the air density, something similar to a mirage over a heated road on a sunny day.

Wallace Clement Sabine pioneered the optical visualization of pressure waves in the field of acoustics. In the 1910s, Sabine built several scale models of theaters and auditoria and then generated shock waves inside the models using fulminate mercury explosions and electric sparks. Sabine was able to obtain surprisingly detailed photographs of the waves reflecting off the surfaces of the scale models using shadowgraphy (Sabine, 1913; see bit.ly/3XlfSiK).

Following Sabine’s experiments, Swiss engineer Franz Max Osswald further developed the technique to photograph sound (Von Fischer, 2017). **Figure 3** shows one of Osswald’s shadowgrams depicting the horizontal cross section of an auditorium model (side view) where the lines within the gray region are the pressure waves radiated by a source (**Figure 3**, black circle). One can clearly see the progression of the wave fronts and how they reflect and diffract from the different surfaces. The type of visualization techniques used by Sabine and Osswald, such as shadowgraphy and schlieren, offered very low sensitivities though, and consequently, their use was limited in the scientific study of acoustics.

The Birth of Acousto-Optics

The work of French physicist Léon Brillouin was a landmark in the field of acousto-optics. In 1922, Brillouin postulated that as light passes through a medium (e.g., a crystal, water, or air), it interacts with waves traveling in that medium (e.g., an acoustic wave) in a very particular way. Specifically, the waves cause the light beam to diffract (Brillouin, 1922).

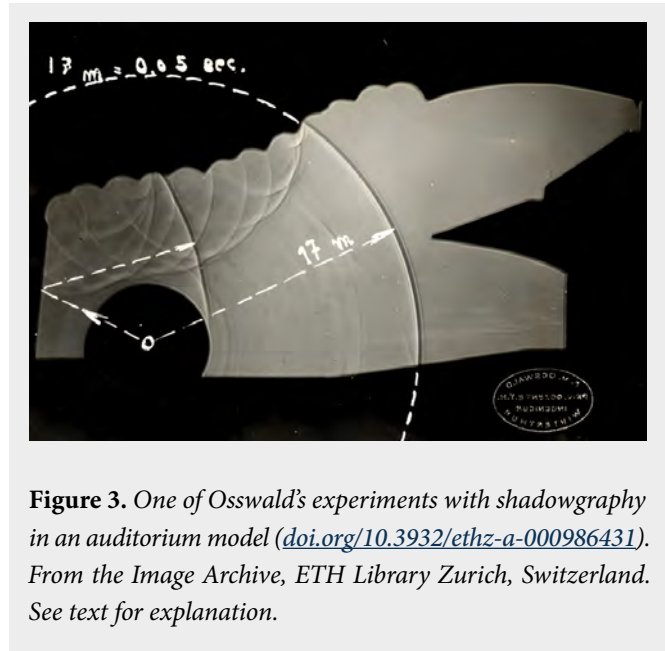


Figure 3. One of Osswald’s experiments with shadowgraphy in an auditorium model (doi.org/10.3932/ethz-a-000986431). From the Image Archive, ETH Library Zurich, Switzerland. See text for explanation.

The diffraction of light by ultrasound was observed for the first time in 1932 by Debye and Sears (1932) in the United States and by Lucas and Biquard (1932) in France. In the 1930s, Indian physicists Raman and Nath (1935) developed the theory for the diffraction of light due to ultrasonic waves, referred to as the acousto-optic diffraction. The first applications of the acousto-optic diffraction coincide with the onset of the use of lasers in the 1960s. A plethora of devices that use sound waves to modulate, deflect, and focus beams were developed, and continue to be widely used today (Adler, 1967).

The Second Half of the Twentieth Century

During the 1960s and 1970s, various visualization methods based on laser interferometry were proposed. Developed in 1965, *holographic interferometry* offered a noncontact way of visualizing the vibration of objects as well as invisible phenomena in transparent media (Vest, 1979). In a double-exposed hologram, the light reflected by an object at two different deformation states was recorded on a single photographic plate so that the reconstructed hologram displayed interference fringes that correspond to the deformation. Holographic interferometry evolved rapidly, yet the process was complicated and time consuming, involving the exposure and development of photographic plates.

The use of electronic recording devices was introduced in the 1970s. In a method called *electronic speckle pattern*

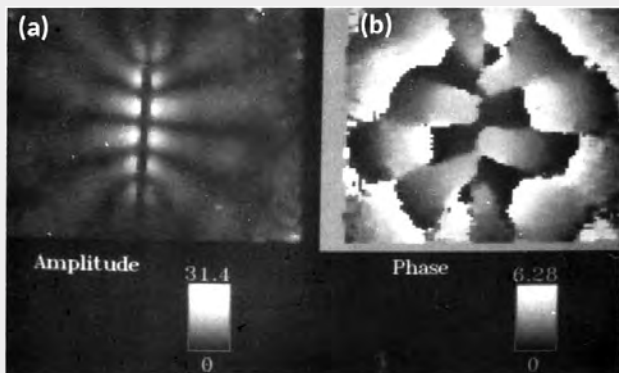
interferometry, a video camera recorded the speckle pattern formed when illuminating an object with coherent light. The recorded images were then processed to visualize the phenomena. The use of digital cameras in the 1980s further advanced the development of imaging techniques. However, it was still difficult to retrieve quantitative information of acoustic pressure waves. It was not until the 1990s and early 2000s that systems sensitive to the amplitude and phase of the acoustic signals began to be adopted.

Figure 4 shows one of such experiments (Løkberg, 1994). The sound field radiated by a vibrating metal plate was recorded using a version of electronic speckle pattern interferometry. The images show a side view (i.e., looking at the plate’s edge) with the amplitude of the projected field seen in **Figure 4a** and the phase seen in **Figure 4b**. This type of quantitative acousto-optic measurement was only possible due to the technological maturity achieved in the 1990s.

The New Century

From the start of the new century, technological developments and research in the field have made it possible to

Figure 4. Visualization of the sound field radiated by a vibrating plate using electronic speckle-pattern interferometry. The **gray scales** represent nanometers for the amplitude (a) and radians for the phase (b). **a:** Plate profile appears as a **black line** in the center. The sound radiated by the plate appears as **white streaks** on the sides of the plate. **b:** Phase map shows phase values increasing linearly from 0 (**black**) to 2π (**white**), indicating the directions in which sound waves are traveling. Reproduced from Løkberg (1994), with permission of the Acoustical Society of America, Copyright 1994.



quantitatively measure, visualize, and reconstruct audible sound of “normal” amplitude. One of the most popular of devices currently used for acousto-optic sensing is the laser Doppler vibrometer (LDV), an interferometer originally designed to measure the vibration velocity of objects (see bit.ly/3Nr2hSq). LDVs are a popular way to measure and visualize acoustic fields (Oikawa et al., 2005), partly because off-the-shelf LDV units are compact and easy to set up compared with other ad hoc interferometric arrangements.

LDVs can provide measurements of a sound field *projected* along a laser beam. Projections of a sound field on a two-dimensional (2D) plane can be also obtained using a scanning LDV, which is a LDV with a set of moving mirrors that can steer the laser beam in multiple directions. Because LDVs essentially provide a single-point measurement, it is necessary to scan the field to obtain 2D projections. Because of this, the visualized sound fields are limited to those that can be generated repeatedly, such as the sound field radiated by a loudspeaker.

In recent years, the use of polarized high-speed cameras has removed the need for scanning LDVs. As the camera captures 2D images of the sound field on thousands of pixels simultaneously, the sound fields that can be measured are no longer limited to those that can be repeated. A high-speed camera captures 2D sound fields with tens or hundreds of thousands of frames per second, making it possible to film a slow-motion video of propagating sound in real time. In particular, parallel phase-shifting interferometry (PPSI) has demonstrated impressive visualizations of airborne acoustic phenomena due to its high sensitivity and spatiotemporal resolution (Ishikawa et al., 2016).

Acousto-Optic Sensing Today Three-Dimensional Sound Field in Rooms with a Laser Doppler Vibrometer

Measuring and visualizing sound fields in three dimensions is central to many aspects of acoustics. However, acquiring sound fields over large volumes of space using conventional microphones is challenging. Acousto-optic sensing provides a remote, noninvasive, and high-resolution way of acquiring volumetric sound fields.

For example, in a recent study (Verburg and Fernandez-Grande, 2021), the 3D sound field inside a reverberant

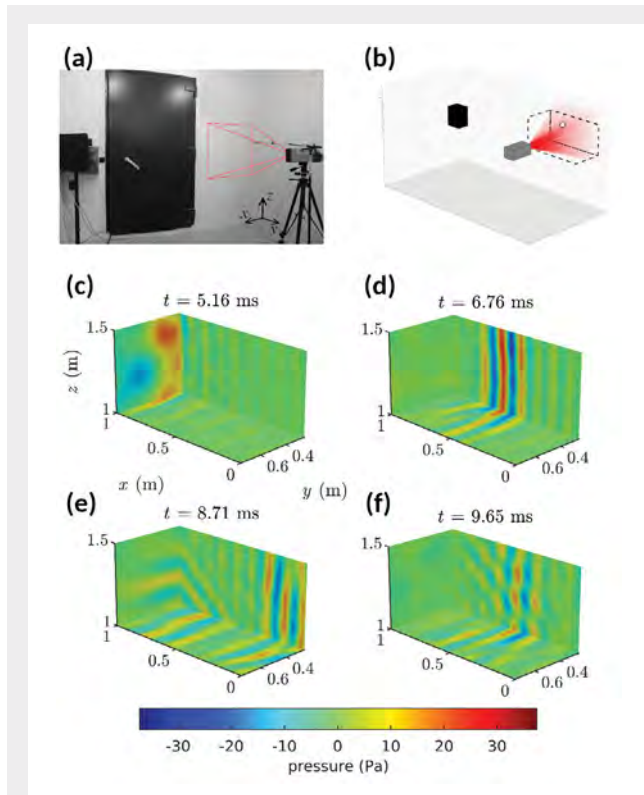


Figure 5. Three-dimensional sound field inside a reverberant room reconstructed from remote acousto-optic measurements. **a and b:** Experimental setup. The LDV (**b**, gray box) was used to acquire acousto-optic measurements of the sound field radiated by a loudspeaker (**a**, black box). The sound field was sequentially scanned over a square-pyramid volume (**red**). The sound field was reconstructed in a $1- \times 0.5- \times 0.5\text{-m}^3$ rectangular volume (**b**, dashed line), and the acoustic pressure is displayed on three planes corresponding to three sides of such volume. **c-f:** Four snapshots of the acoustic pressure over time. **c:** Sound arriving from the source. **d:** Wavefront as it travels. **e:** Two reflections, one from a wall and one from the floor. **f:** Interference pattern between the two reflections. The color map represents the amplitude of the acoustic pressure. Reproduced from Verburg and Fernandez-Grande (2021), with permission of the American Physical Society, Copyright 2021.

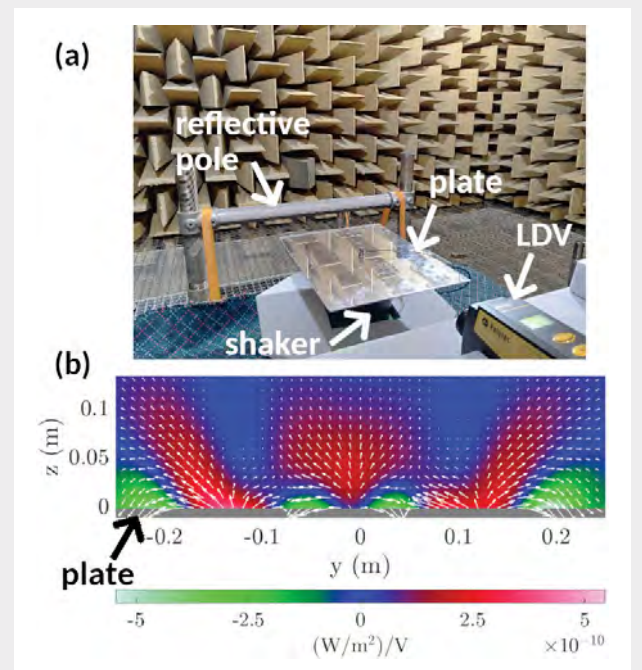
room was reconstructed from acousto-optic measurements using a scanning LDV (Figure 5a, b). The LDV (Figure 5b, gray box) was used to acquire acousto-optic measurements of the sound field radiated by a loudspeaker (Figure 5b, black box). Figure 5c-f corresponds to four snapshots of the acoustic pressure over time (see bit.ly/44wgbKm for a video).

Near-Field Acoustic Holography with a Laser Doppler Vibrometer

Near-field acoustic holography (NAH) is a powerful technique that makes it possible to examine and visualize how acoustic sources radiate sound into the medium. In NAH, the sound pressure near a source is normally measured using an array of microphones. However, at high frequencies, the microphone spacing needs to be increasingly small, and the sound scattering due to many closely spaced microphones introduces significant measurement errors (i.e., the microphone array can no longer be assumed to be “acoustically transparent”).

The use of acousto-optic sensing for near-field measurements has recently been examined as a noninvasive alternative to conventional microphones by Verburg et al. (2022). The experimental setup of this study is shown in Figure 6a. The acoustic pressure at 3.5 cm above a

Figure 6. Optical measurements of the sound field above a vibrating plate. **a:** Experimental setup. LDV, laser Doppler vibrometer. **b:** Intensity field above the plate. **White arrows:** direction and amplitude of the vector intensity field. The color map indicates the amplitude of the intensity field in the direction normal to the plane. Reproduced from Verburg et al. (2022), with permission of the Acoustical Society of America, Copyright 2022.



vibrating aluminum plate was optically measured using a LDV. The plate was mounted on a shaker to excite vibrations. The laser beam was directed at a steel reflective pole covered with retroreflective tape. The setup was installed inside an anechoic chamber.

As an example, **Figure 6b** shows the sound intensity field (i.e., the flow of acoustic energy) *above* the plate when it was vibrating at a resonance frequency. To visualize how the plate radiates sound energy into the medium, **Figure 6b** shows a vertical cross section passing through the center of the plate (the x - y plane with $z = 0$ corresponds to the position of the plane). It is possible to observe complex radiation phenomena such as the nonpropagating circulation of acoustic intensity close to the plate. Such fine details are difficult to capture using conventional microphone arrays, especially at mid- and high frequencies.

Aeroacoustics and Moving Sources with Parallel Phase-Shifting Interferometry

Measuring sound fields in the presence of airflow with conventional microphones is very challenging. First, introducing a device in the measurement area will undoubtedly disturb the airflow. And second, the flow of air around the microphone will generate a high noise (we have all tried to have a phone call on a windy day). Acousto-optic sensing is suitable for measuring sound fields in the presence of airflow; because light is the sensing element, no physical device is introduced in the measurement area. Interestingly, the technique enables one to observe acoustic waves and the fluid dynamics simultaneously, a practice that is not possible with conventional acoustic instrumentation.

Figure 7 visualizes both the airflow and the sound waves emitted from a whistle using PPSI and a high-speed camera (Ishikawa et al., 2018) (see bit.ly/3XWkFaG for a video). At 0 ms, we can start to see the flow of air coming from the opening of the whistle. As time progresses, the turbulent flow develops, showing a seemingly chaotic structure. At 33.3 and 38.1 ms, a spherical acoustic wave radiating from the whistle opening can clearly be seen. It is interesting to observe that the two types of perturbation (acoustic and flow) present very different temporal and spatial scales. The airflow evolves more rapidly and presents a finer structure over space. The combined analysis of flow and acoustic waves is only possible due to the recent advances in acousto-optic sensing and PPSI.

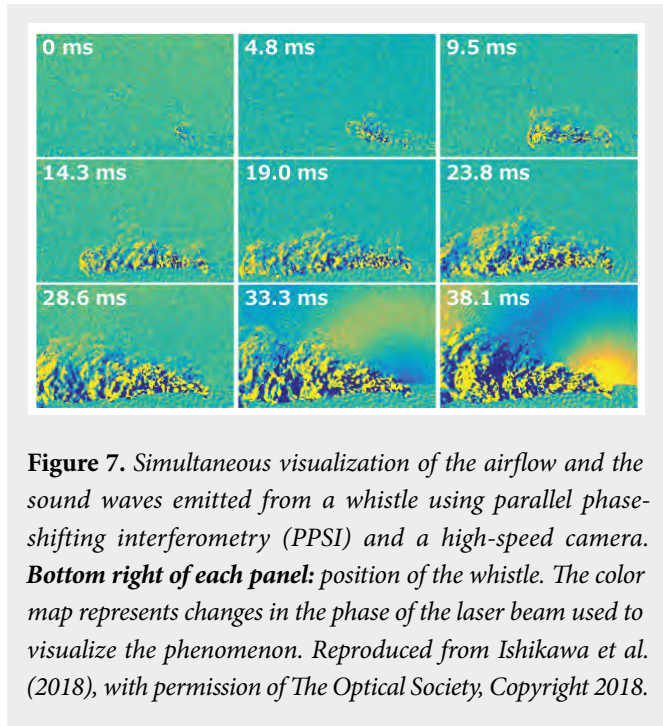


Figure 7. Simultaneous visualization of the airflow and the sound waves emitted from a whistle using parallel phase-shifting interferometry (PPSI) and a high-speed camera. **Bottom right of each panel:** position of the whistle. The color map represents changes in the phase of the laser beam used to visualize the phenomenon. Reproduced from Ishikawa et al. (2018), with permission of The Optical Society, Copyright 2018.

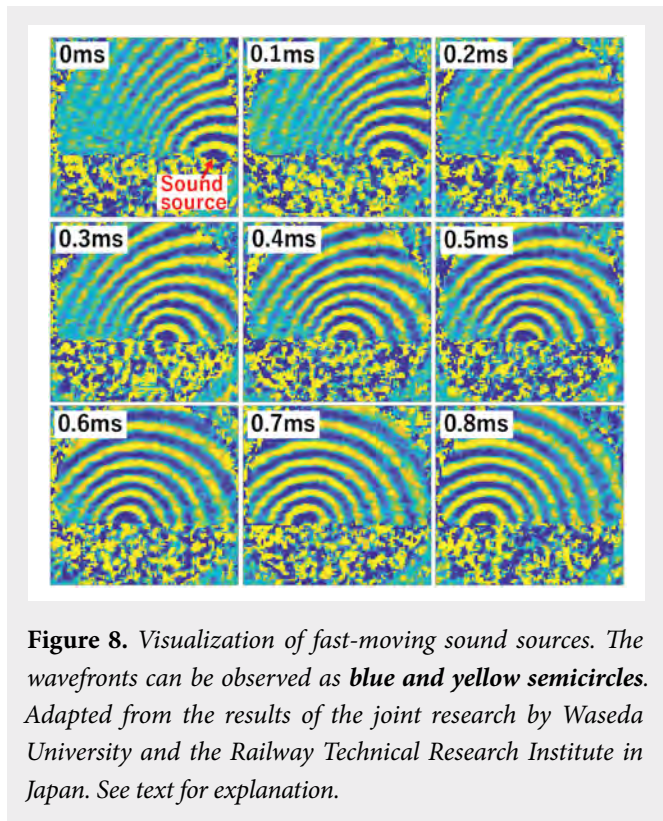


Figure 8. Visualization of fast-moving sound sources. The wavefronts can be observed as **blue and yellow semicircles**. Adapted from the results of the joint research by Waseda University and the Railway Technical Research Institute in Japan. See text for explanation.

A related application is the visualization of fast-moving sound sources such as high-speed trains. A fast-moving source generates airflow itself, and the acoustic pressure that it radiates is difficult to capture. In a recent

study, Akutsu et al. (2022) used PPSI to visualize the sound field generated by the scale model of a train. A sound source was flush mounted on the scale model and launched at a speed of 280 km/h (174 mph). The source was emitting a pure tone of 40 kHz. **Figure 8** shows the resulting phase changes of light captured with a high-speed camera (see bit.ly/46S5CmG for a video). As the sound source travels from right to left, the wavefronts are “compressed” in front of the model and “expand” at the back. This behavior, known as the Doppler effect, is typical of moving sources.

Acoustic Metrology with Light

Acoustic metrology is the area of acoustics that deals with the definition of measurement units (e.g., the Pascal in the case of acoustic pressure) as well as the traceability and calibration of measurement devices. Although several standardized methods exist to calibrate acoustic measurement devices, none of them is free of limitations.

One common calibration method is the *free-field calibration* in which a pair of microphones are positioned facing each other at a fixed distance in a free field (e.g., an anechoic chamber). A major source of uncertainty in free-field calibration is knowing the exact distance between the *acoustic center* of both microphones (which is different from the physical distance between them). Her-mawanto et al. (2023) were able to determine the acoustic center of a microphone with high accuracy, leveraging the noncontact nature of acousto-optic sensing.

In the past, the relatively high noise level of optical measurements hindered their application to acoustic metrology. However, recent advances in acousto-optic measurements have achieved equivalent noise levels of 0 dB sound pressure level (SPL)/Hz (Ishikawa et al., 2021), which is comparable with standard high-precision measurement microphones. It all seems to indicate that optical measurements will play a crucial role in next-generation acoustic metrology due to their precision, universality, and noncontact nature.

Other Applications

Acousto-optic sensing has found multiple other applications in recent years, just a few of which are discussed now. One of the aims of research in bioacoustics is to reveal the mechanisms by which animals generate sound because this sheds light on the evolutionary processes

of the animals that produce it. It is sometimes difficult to measure and visualize such bioacoustic signals, and acousto-optic sensing can help to do so. Optical, non-contact PPSI measurements have recently been used to visualize the sound generated by the cicada (*Tanna japonensis*), a sound-producing insect (Oikawa et al., 2018) (see bit.ly/3DjQq45). This type of visualizations can be used to observe the spatial and temporal features of bioacoustic signals, deepening our understanding of how animals produce sound. Other videos of acoustic phenomena captured using PPSI can be seen on Professor Oikawa’s laboratory YouTube channel at bit.ly/3rrsUzq.

The high spatial and temporal resolution offered by PPSI as well as its noncontact nature make it a convenient tool to investigate the sound radiation from musical instruments. For example, Ishikawa et al. (2020) investigated the sound produced by *castanets*, a small percussion instrument used in traditional Spanish music. The castanets are composed of two wooden shells that produce a strong clapping sound when played. Because of the way it is constructed, no measurement device can be placed in between the two shells where the sound resonates. Due to the noncontact nature and high resolution of optical measurements, it was possible to unveil the sound-generation mechanism of castanets (see bit.ly/3Di1mil). A better understanding of the mechanisms in which musical instruments generate sound can help us craft better sounding and more-durable instruments as well as guide us in the restoration of historical instruments.

Acousto-optic sensing can also help address long-standing problems in engineering acoustics, such as the characterization of acoustically absorptive materials. Classrooms, hospitals, and offices are usually treated with acoustic panels that absorb unwanted sound. A common way of quantifying the absorption of the acoustic materials used for the panels is the *impedance-tube* method. The method consists of placing a sample of the material on one end of a rigid tube while sound waves are generated with a loudspeaker placed on the other end. The sound energy absorbed by the sample is then monitored with a pair of microphones mounted on the tube’s wall. However, the impedance-tube frequency range of operation is limited by the tube’s width. Acousto-optic sensing has made it possible to largely extend this frequency range, facilitating the characterization of acoustic materials. Vanlanduit et al. (2005) measured the sound field inside

a transparent tube using a LDV and characterized different materials. Because the sensing element (light) does not interfere with the acoustic field, tubes narrower than the standard ones could be used, effectively extending the frequency range of validity.

Outlook

Although it might still be a relatively unknown technique, we expect to see a broader understanding and use of acousto-optic sensing in the acoustics community. After all, many fields within acoustics can benefit from remote, noninvasive acoustic measurements and visualizations. For instance, optical visualization of sound can be directly applied to, for example, education, musical acoustics, and bioacoustics where the visualization of invisible phenomena can help build an intuition.

The measurement and visualization of sound using light is a relatively new area that has an extraordinary potential for exploration across the field of acoustics. State-of-the-art acousto-optic measurements are already able to achieve very low noise levels as well as render detailed visualizations. Further technological advances will make it possible to address long-standing acoustic problems, find new applications, and unveil complex acoustic phenomena. In particular, the field of *quantum photonics* is experiencing a very rapid development, with increasing capabilities to generate, manipulate, and detect light at the level of individual quanta. Detectors can count individual photons, and ultrafast lasers can send femtosecond (10^{-15} s) light pulses, thus pushing the limits of what is possible in experimental physics. It will be exciting to see how acousto-optic sensing benefits from these advances in the near future.

References

- Adler, R. (1967). Interaction between light and sound. *IEEE Spectrum* 4, 42-54. <https://doi.org/10.1109/MSPEC.1967.5215753>.
- Akutsu, M., Uda, T., Kohei, Y., and Oikawa, Y. (2022). Visualization of sound waves around high-speed moving source using parallel phase-shifting interferometry. *Proceedings of the 24th International Congress on Acoustics ICA 2022*, Gyeongju, Republic of Korea, October 24-28, 2022.
- Brillouin, L. (1922). Diffusion de la lumière et des rayons X par un corps transparent homogène. *Annales de Physique* 9.17, 88-122. <https://doi.org/10.1051/anphys/192209170088>.
- Debye, P., and Sears, F. W. (1932). On the scattering of light by supersonic waves. *Proceedings of the Natural Academy of Sciences* 18, 409-414. <https://doi.org/10.1073/pnas.18.6.409>.
- Feynman, R., Leighton, R. B., and Sands, M. (1964). The origin of the refractive index. *The Feynman Lectures on Physics*, Addison-Wesley, Boston, MA. Available at https://www.feynmanlectures.caltech.edu/I_31.html. Accessed June 8, 2023.
- Hermawanto, D., Ishikawa, K., Yatabe, K., and Oikawa, Y. (2023). Determination of microphone acoustic center from sound field projection measured by optical interferometry. *The Journal of the Acoustical Society of America* 153, 1138-1146. <https://doi.org/10.1121/10.0017246>.
- Ishikawa, K., Shiraki, Y., Moriya, T., Ishizawa, A., Hitachi, K., and Oguri, K. (2021). Low-noise optical measurement of sound using midfringe locked interferometer with differential detection. *The Journal of the Acoustical Society of America* 150, 1514-1523. <https://doi.org/10.1121/10.0005939>.
- Ishikawa, K., Tanigawa, R., Yatabe, K., Oikawa, Y., Ikeda, Y., Oikawa, Y., Onuma, T., Niwa, H., and Yoshii, M. (2018). Simultaneous imaging of flow and sound using high-speed parallel phase-shifting interferometry. *Optics Letters* 43, 991-994. <https://doi.org/10.1364/OL.43.000991>.
- Ishikawa, K., Yatabe, K., and Oikawa, Y. (2020). Seeing the sound of castanets: Acoustic resonances between shells captured by high-speed optical visualization with 1-mm resolution. *The Journal of the Acoustical Society of America* 148, 3171-3180. <https://doi.org/10.1121/10.0002446>.
- Ishikawa, K., Yatabe, K., Chitanont, N., Ikeda, Y., Oikawa, Y., Onuma, T., Niwa, H., and Yoshii, M. (2016). High-speed imaging of sound using parallel phase-shifting interferometry. *Optics Express* 24, 12922-12932. <https://doi.org/10.1364/OE.24.012922>.
- Kilgour, F. G. (1963). Vitruvius and the early history of wave theory. *Technology and Culture* 4, 282-286. <https://doi.org/10.2307/3100857>.
- Løkberg, O. J. (1994). Recording of sound emission and propagation using TV holography. *The Journal of the Acoustical Society of America* 96, 2244-2250. <https://doi.org/10.1121/1.410096>.
- Lucas, R., and Biquard, P. (1932). Optical properties of solids and liquids under ultrasonic vibrations. *Journal de Physique et Le Radium* 7, 464-477. <https://doi.org/10.1051/jphysrad:01932003010046400>.
- Oikawa, Y., Goto, M., Ikeda, Y., Takizawa, T., and Yamasaki, Y. (2005). Sound field measurements based on reconstruction from laser projections. *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing, ICASSP 2005*, Philadelphia, PA, March 23, 2005. <https://doi.org/10.1109/ICASSP.2005.1416095>.
- Oikawa, Y., Ishikawa, K., Yatabe, K., Onuma, T., and Niwa, H. (2018). Seeing the sound we hear: optical technologies for visualizing sound wave. *Proceedings of the SPIE Commercial and Scientific Sensing and Imaging*, Orlando, FL, April 16-17, 2018., pp. 106660C:1-8. <https://doi.org/10.1117/12.2305323>.
- Raman, C. V., and Nath, N. S. N. (1935). The diffraction of light by high frequency sound waves: Part I. *Proceedings of the Indian National Science Academy* 2, 406-412. <https://doi.org/10.1007/BF03035840>.
- Sabine, W. C. (1913). Theater acoustics. *The American Architect* 104, 271.
- Settles, G. S. (2001). *Schlieren and Shadowgraph Techniques: Visualizing Phenomena in Transparent Media*. Springer-Verlag, Berlin Heidelberg, Germany.
- Torrás-Rosell, A., Barrera-Figueroa, S., and Jacobsen, F. (2012). Sound field reconstruction using acousto-optic tomography. *The Journal of the Acoustical Society of America* 131, 3786-3793. <https://doi.org/10.1121/1.3695394>.
- Vanlanduit, S., Vanherzeele, J., Guillaume, P., and De Sitter, G. (2005). Absorption measurement of acoustic materials using a scanning laser Doppler vibrometer. *The Journal of the Acoustical Society of America* 117, 1168-1172. <https://doi.org/10.1121/1.1859233>.
- Verburg, S. A., and Fernandez-Grande, E. (2021). Acousto-optical volumetric sensing of acoustic fields. *Physical Review Applied* 16(4), 044033. <https://doi.org/10.1103/PhysRevApplied.16.044033>.

A CENTURY OF ACOUSTO-OPTICS

Verburg, S. A., Fernandez-Grande, E., and Williams, E. G. (2022). Acousto-optic holography. *The Journal of the Acoustical Society of America* 152, 3790-3799. <https://doi.org/10.1121/10.0016627>.
 Vest, C. M. (1979). *Holographic Interferometry*. Wiley, New York.
 Von Fischer, S. (2017). A visual imprint of moving air: Methods, models, and media in architectural sound photography, ca. 1930. *Journal of the Society of Architectural Historians* 76, 326-348. <https://doi.org/10.1525/jsah.2017.76.3.326>.

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