Non-intrusive sound pressure measurement using light scattering

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(Received 12 December 2014, Accepted for publication 20 April 2015)

Abstract: Light propagating through a sound field is affected by variations in the density of the medium caused by sound. Therefore, acoustical measurements using light have been studied. The popular measurement methods use the phase shift of the transmitted light. Because they detect integrated acoustical quantities along the optical path of the detected light, time and effort are required to measure the quantities at a single point. On the other hand, single-point acoustical particle velocity measurement by light scattering has been proposed. Using light scattering enables the measurement of non-integrated quantities because the scattered light includes only the acoustical information at a scattering point. However, a method of non-invasive sound pressure measurement at a single point in a free field has not been established. This paper proposes sound pressure measurement at a scattering point, in which the light scattered by particles in the sound field is observed. The intensity of light scattered in the sound field indicates the sound pressure because the intensity of the scattered light is proportional to the density of scatterers. The theory of light scattering by sounds is formalized, and sound measurement experiments with light scattering are also conducted using water drops and air particles as scatterers.

Keywords: Light scattering, Acoustical metrology, Optical measurement

PACS number: 43.20.Ye, 43.58.Fm [doi:10.1250/ast.36.408]

1. INTRODUCTION

Sound measurements using light have been studied in various fields of acoustical engineering. The measurements do not affect the measurement field because there is no instrument in the field. In such measurements, the acoustical quantities are captured by detecting the transmitted, reflected, or scattered light that is emitted to the field. The variation in the refractive index of air causes variation in the speed of light and the intensity of scattered light. Because the refractive index is changed by sounds, sound measurements can be made by detecting the light.

Popular methods are the use of the phase shift or diffraction of the transmitted light. For example, the sound pressure along the optical light path is measured using a laser Doppler vibrometer, which detects the phase shift of the received light [1–7]. The optical wave microphone uses light diffraction to measure sounds [8]. However, the quantities measured by these methods are integrated along the optical path because the light passing through the sound field is observed. Therefore, additional effort is required to extract information at a single point.

Obtaining 3D sound field measurements by applying computed tomography to those optical methods has been studied. By measuring the projections of the sound field from all directions, the 3D field can be reconstructed. In some cases, however, measuring the field from all directions requires time and effort.

On the other hand, the methods using light scattering can measure the acoustical properties at a single point directly. Acoustical particle velocity measurements using the Doppler effect of scattered light have long been studied [9,10]. Rausch et al. measured the standing waves in an acoustical duct with sound pressures of 25 to 150 Pa using scattering by air particles, although free-field audible sound pressure measurement was not considered [11].

In this paper, we propose sound pressure measurements in the free field using light scattering, which enables measurement of the non-integrated sound pressure. We derive the relation between the sound and the scattered light, and we formalize the theory of light scattering in acoustical measurements. Two types of scatterers, water drops and air particles, are considered, and fundamental experiments using those scatterers are conducted.
2. SCATTERING THEORY

2.1. Light Scattering

Light scattering, that is, the diffusion of incident light by particles, is categorized into two types: elastic scattering and inelastic scattering. In elastic scattering, the sum of the kinetic and internal energies is not changed by scattering. On the other hand, in inelastic scattering, the energy changes after scattering.

Scattering caused by air particles which are influenced by sound is elastic scattering. It depends on the ratio of the wavelength of the incident light to the radius of the scatterers. The size parameter $a$, which is often used for parameterizing the radius of the scatterers, is represented as

\[ a = \frac{2\pi d}{\lambda}, \]

where $d$ is the radius of the scatterers, and $\lambda$ is the wavelength of the light. The scattering when $a$ is much smaller than 1 is called Rayleigh scattering and is caused by nitrogen and oxygen molecules in the atmosphere. The scattering when $a$ is nearly equal to 1 is called Mie scattering and is caused by aerosols. Because the scattering is characterized by the intensity and scattering cross section, we calculate those values for Rayleigh and Mie scattering.

2.2. Mie Scattering

Mie solved the equation for a homogeneous spherical particle and a monochromatic plane wave in 1908 [12,13]. The scattering intensities of horizontally and vertically polarized light, $I_1(\theta)$ and $I_2(\theta)$, respectively, are

\[ I_1(\theta) = \frac{\lambda^2}{4\pi^2 r^2} |A_1(\theta)|^2, \]
\[ I_2(\theta) = \frac{\lambda^2}{4\pi^2 r^2} |A_2(\theta)|^2, \]

where $r$ is the distance between the scattered point and the observed point, $\theta$ is the angle formed by the incident and scattered light, $A_1(\theta)$ and $A_2(\theta)$ are the amplitude functions of horizontally and vertically polarized light, respectively. $A_1(\theta)$ and $A_2(\theta)$ are given by

\[ A_1(\theta) = \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} [a_n \xi_n(\cos \theta) + b_n \chi_n(\cos \theta)], \]
\[ A_2(\theta) = \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} [a_n \chi_n(\cos \theta) + b_n \xi_n(\cos \theta)], \]

where $a_n$ and $b_n$ are coefficients, and $\xi_n$ and $\chi_n$ are angular functions. They are given as follows:

\[ a_n = \frac{\psi_n(a) \psi'_n(ma) - m \psi_n(ma) \psi'_n(a)}{\xi_n(a) \psi'_n(ma) - m \psi_n(ma) \xi'_n(a)}, \]
\[ b_n = \frac{m \psi_n(a) \psi'_n(ma) - \psi_n(ma) \psi'_n(a)}{m \xi_n(a) \psi'_n(ma) - \psi_n(ma) \xi'_n(a)}, \]
\[ \xi_n(\cos \theta) = \frac{P^{(1)}_n(\cos \theta)}{\sin \theta}, \]
\[ \chi_n(\cos \theta) = \frac{d}{d\theta} P^{(1)}_n(\cos \theta), \]

where $\lambda$ is the wavelength of the incident light, $r$ is the distance between the scattering point and the measuring point, $m$ is the relative refractive index, $\psi_n(a)$ is the Riccati–Bessel function, $\xi_n(\alpha)$ is the Hankel function of the first kind, $P^{(1)}_n(\cos \theta)$ is the associated first-order Legendre function, and $f'$ is the derivation of function $f$.

The scattering cross section $\sigma$, which is defined as the number of photons scattered when a single photon collides with a single scatterer per unit area and unit time, is

\[ \sigma = \frac{\lambda^2}{4\pi} \int_0^\pi (|A_1(\theta)|^2 + |A_2(\theta)|^2) \sin \theta d\theta. \]

When we substitute $A_1$ and $A_2$ from Eqs. (4) and (5), respectively, $\sigma$ becomes

\[ \sigma = \frac{\lambda^2}{2\pi} \sum_{n=1}^{\infty} (2n+1) |a_n|^2 + |b_n|^2. \]

2.3. Rayleigh Scattering

When the size parameter is much smaller than 1, the intensity and scattering cross section of the scattering have simpler forms. Because scattering by particles with diameters much smaller than the wavelength of the incident light can be considered as radiation from a single dipole oscillating under an applied electromagnetic field, the scattering equation is modified to a simple form by an appropriate approximation [14]. When a plane wave is incident on a homogeneous particle, the scattering intensity at distance $r$ is

\[ I_1(\theta) = \frac{16\pi^4 \alpha^6}{\lambda^4 r^2} \left| \frac{m^2 - 1}{m^2 + 1} \right|^2, \]
\[ I_2(\theta) = \frac{16\pi^4 \alpha^6}{\lambda^4 r^2} \left| \frac{m^2 - 1}{m^2 + 1} \right|^2 \cos^2 \theta, \]

where $I_1$ is the horizontally polarized light, $I_2$ is the vertically polarized light, and $k$ is the wavenumber. The intensity of Rayleigh scattering is proportional to the sixth power of the diameter of the particle and the negative fourth power of the wavelength of the incident light. When the incident light is unpolarized, the intensity $I_{12}$ and scattering cross section $\sigma$ are written as

\[ I_{12}(\theta) = \frac{8\pi^4 \alpha^6}{\lambda^4 r^2} \left| \frac{m^2 - 1}{m^2 + 1} \right|^2 (1 + \cos^2 \theta), \]
\[ \sigma = \frac{128\pi^4 \alpha^6}{3 \lambda^4} \left| \frac{m^2 - 1}{m^2 + 2} \right|^2. \]
the ratio of the intensity of scattered light to that of incident light; the number density is the number of scattering points per unit volume; \( I \) is the intensity of the scattered light; and \( I_0 \) is the intensity of the incident light. The number density is

\[
N = \frac{\rho}{M},
\]

(17)

where \( M \) and \( \rho \) are the molecular weight and density of the scatterers, respectively. The density \( \rho \) is approximately

\[
\rho = \rho_0 \left( 1 + \gamma \frac{p}{p_0} \right),
\]

(18)

where \( \rho_0 \) and \( p_0 \) are the density and the pressure under static conditions, \( \gamma \) is the specific heat ratio, \( p \) is the sound pressure. Therefore, when Eqs. (17) and (18) is substituted into Eq. (16), the scattered light intensity becomes

\[
I(\theta) = \frac{V}{R^2 M} \left( 1 + \gamma \frac{p}{p_0} \right) \frac{d\sigma(\theta)}{d\Omega} I_0.
\]

(19)

The differential scattering cross section is the scattering cross section into angle \( \theta \). In other words, the scattering cross section, which depends on the wavelength of the incident light, the diameter of the scatterer, and the refractive index, is the integrated value of the differential scattering cross section with respect to the angle. When we consider an actual measurement system, the wavelength of the incident light and the diameter of the scatterer can be assumed to be constant. If the light source and receiving optics do not move, the angle formed by the incident light and optics is also constant. Thus, from Eq. (19), we can measure the sound pressure from the intensity fluctuation of the scattered light.

3. FORMULATION OF SCATTERED LIGHT FOR ACOUSTICAL MEASUREMENT

In this section, we derive the effect of the scattering coefficient of the received light when the incident light is emitted to a sound field and the scattered light is detected. A basic setup of sound measurement equipment based on the theories described in the previous section is considered, and a theoretical evaluation is conducted. The equipment should be arranged so that the effect of its presence can be ignored as much as possible to maintain the advantage of non-intrusive sound measurement. A laser is used as a light source because a narrow beam is required to limit the measuring area. However, the light source can be any arbitrary source that emits a narrow beam because this method does not require coherent light.

Next, the receiving component is described. Because the observed scattered light is transduced to an electrical signal, a photoelectric transducer is used. In addition, a telescope is used to efficiently observe the scattered light from the desired direction. The telescope is arranged in front of the photoelectric transducer so that the scattering point is in the field of view of the telescope. Placing the photoelectric transducer at the focal point of the telescope makes it possible to detect the light scattered from the
direction of the telescope’s field of view efficiently. Signal processing after the light is detected is not considered in this section.

3.1. Single-point Scattering

The incident light scattered and observed at one point is considered. We defined the coordinates as shown in Fig. 2. The distance between the origin and \( x \) is \( R_1 \), and that between \( x \) and \( y \) is \( R_2 \). When the scattering volume is 1, the observed light power \( P \) is

\[
P = P_m \frac{T(R_1 + R_2)}{R_2^2} \beta(\theta),
\]

where \( P_m \) is the incident light power, \( T \) is the atmospheric transmissivity, \( \theta \) is the angle formed by the incident and scattered light, and \( \beta \) is the scattering coefficient. The atmospheric transmissivity, which is the ratio of the intensities of the incident and transmitted light, is

\[
T(R) = e^{-\int_a^R \alpha(r)dr},
\]

where \( R \) is the propagation distance of the light, and \( \alpha \), which is called an extinction coefficient, is the sum of the scattering and absorption coefficients [17]. Although the extinction coefficient is generally a function of attitude, the attitude of the light path for sound measurement can be assumed to be constant. Changes in the coefficient due to wind and temperature fluctuations can be ignored because the frequencies are low enough to be distinguished from audible sound frequencies.

3.2. Volume Scattering

The scattering area and observation area are not points but have a certain area in actual measurement. Thus, the coordinate system shown in Fig. 3 is considered. The position of the light source is regarded as constant because the light source is fixed at one point during the measurement. Scattering occurs in the volume where the incident light and scatterers are present, which is defined as \( V \). On the other hand, the observation area is regarded as a plane, which is defined as \( S \), because that is how it appears to the lens or mirror of the telescope.

The total power of the scattered light on the observed plane, \( P \), is

\[
P = \int_S \int_V P_m(t - R_1(x)/c)
\frac{T(R_1(x) + R_2(x,y))}{R_2^2(x,y)^2} \beta(\theta(x,y))dxdy,
\]

where \( x \in V, y \in S, c \) is the speed of light, and \( t \) is the time at which scattering occurs. The incident laser light power \( P_m \) is a function of time. The independent variable of \( P_m \) is \( R_1(x)/c \), in units of seconds before the observation time \( t \), because the light that exists at point \( x \) at time \( t \) was emitted at time \( t - R_1(x)/c \).

4. MEASUREMENT WITH TRACERS USING A CONTINUOUS WAVE LASER

Because the scattering intensity of Mie scattering is much larger than that of Rayleigh scattering, measurement by Mie scattering, which is achieved by using appropriate tracers as scatterers, enables us to measure the sound at the scattering point with a low-power laser. This section describes sound measurement using water drops generated by a humidifier as tracers. Hence, this experiment is not non-intrusive but for confirming the validity of the proposed method. In this case, the scattering caused by air particles can be regarded as zero. The aim of this experiment is to verify the possibility of sound acquisition via light scattering. The behavior of water drops in the sound field is described in [18–20].

4.1. System

The experimental configuration is shown in Fig. 4. Water drops with diameters of about 3 μm were expelled by the humidifier near a measuring point. Laser light was emitted toward the water drops to cause Mie scattering. The telescope, which was located 16 m from the measuring point, was used to concentrate the scattered light and reject the light from undesired directions. The light was detected by a photomultiplier tube (PMT) at the focal position of the telescope. The diameter of the telescope was 27.9 cm.
Because the scattering volume, which is the area where the light and tracers interact, is much smaller than the telescope diameter, we assume that the scattered intensity of all the points in the volume is the same. The incident laser light intensity \( P_{\text{in}} \) is regarded as constant because a continuous wave (CW) laser was used. Therefore, the intensity of the detected light in this system is

\[
P = \eta \frac{P_{\text{in}} V}{R^2} \int \beta(\theta(x,y)) dy,
\]

where \( \eta \) is the efficiency of the optical equipment. Here, the atmospheric transmissivity is ignored because it is greater than 99% when the distance between the scattering point and the receiving optical instruments is 16 m.

### 4.2. Method

Speaker-1, which was placed near the measuring point, generated sine waves of 1, 2, 4, or 8 kHz. Speaker-2, which was placed between speaker-1 and the optics, generated a sine wave of 440 Hz. The sound pressure level of the sounds of the single speakers was 94 dB. Because the scattering caused by tracers is Mie scattering, the amount of light scattered by air particles is negligibly small in this experiment. Therefore, the detected sound should be generated by speaker-1 but not by speaker-2. The optical system may be vibrated by the sound waves, causing the resulting sound pressure to be detected as vibration of the optics. To ensure that the optical equipment is not vibrated by the sound waves, the duration of sound from each source was 20 ms, and the corresponding received signals were analyzed. Because sound propagates 6.8 m during 20 ms, the sound does not reach the optics and another speaker within 20 ms.

A laser with a wavelength of 445 nm and power of 2 W was used.

### 4.3. Results

Figure 5 plots the frequency characteristics of the scattered light when fog was emitted by the humidifier and no sound was generated by the speakers. The graph shows the output ratio of the frequency characteristics of the scattered light with and without the fog. It indicates that the frequency of fluctuations in the density of the fog is concentrated under 20 Hz. Figure 6 depicts the power spectrum density and 95% confidence interval of the average of 200 signals output by the PMT. Welch’s method was used to estimate the power spectrum density [21]. The calculation conditions are shown in Table 1. According to the figures, the outputs of the PMT include the sound generated by speaker-1. As the frequency generated by the speaker-1 increases, the power of the signals decreases. It can be attributed to the decrease of the followability of the fog to the sounds. Because the sound generated by speaker-2 was not detected by the PMT, the intensity fluctuation of the scattered light includes only the sound information at the scattering point.

### 5. MEASUREMENT WITHOUT TRACERS USING A PULSED LASER

#### 5.1. System

5.1.1. Non-integrated value measurement with pulsed light

Figure 7 schematically illustrates the detection of light scattered by air particles using a CW laser and a pulsed laser. If we use the CW laser as the light source, the detected value is the sum of the scattered light from all points on the optical path of the laser beam because scattering by air particles occurs wherever light and air are present. On the other hand, if we use the pulsed laser, the value is not integrated because scattering occurs only where the emitted pulsed light is present. Although the scattering area is limited when pulsed light is used, it is necessary to consider the effect of sound waves on the optical path to measure the sound pressure only at a scattering point. If the transmitted light is affected...
by the sound, because the detected light indicates the sound pressure at not only the scattering point but also at all points where the detected light passed, we cannot acquire the non-integrated quantity. Thus, we consider the intensity variation in the transmitted light caused by sound waves where the light passed through.

As shown in Appendix, the ratio of the variation of the received light power caused by sound at a scattering point and on a unit length of an optical path except the scattering point is

\[
P_{\text{ratio}} = \frac{p}{p_0} e^{-\gamma \frac{p}{\gamma p_0}} - 1
\]

(24)

where \( p_0 \) is the pressure under static conditions, \( p \) is the sound pressure, \( \gamma \) is the specific heat ratio, and \( \beta_0 \) is the static scattering coefficient. The scattering coefficient of the US standard atmosphere is \( 7.5 \times 10^{-5} \) when the wavelength of the incident light is 350 nm [22]. When \( p = 1 \) Pa, \( p_0 = 101,325 \) Pa and \( \gamma = 1.41 \), the ratio becomes

\[
10 \log_{10} |P_{\text{ratio}}| = 41.2 \text{ [dB]},
\]

(25)

which indicates that the effect of the fluctuation of the scattered light due to sound on the optical path is smaller than that at the scattering point.

5.1.2. Sound measurement by backscattered pulsed light

The sound pressure can be measured at any point on the optical light path when the backscattered pulsed light is observed. The pulsed light is emitted to the measurement field, and the backscattered light is collected by a telescope and detected by a photodetector. This phenomenon is used

Fig. 6 Power spectrum density of average of 200 signals calculated by Welch’s method when speaker-1 generated (a) 1 kHz, (b) 2 kHz, (c) 4 kHz, and (d) 8 kHz sine waves. The calculation conditions are shown in Table 1. Solid lines are averaged values; gray regions surrounded by dashed lines show 95% confidence intervals. The plotted values are relative to the reference signal, which is the value when no sound is generated by the speakers.

Table 1 Conditions of power spectrum density calculation using Welch’s method.

| Number of samples | 3,840 |
|-------------------|-------|
| Window type       | Hamming window |
| Window length     | 1,800 |
| Overlap percentage| 50%   |
| Confidence level  | 95%   |

Fig. 7 Sketch of difference in scattering behavior between (a) continuous light and (b) pulsed light when scatterers are air particles. Because scattering occurs at the points where the light is present, the continuous light is scattered at all points on the path. On the other hand, the pulsed light is scattered only within a limited volume that is determined by the laser beam diameter and pulse width.
in light detection and ranging, which is well known as a weather observation system in atmospheric science [17, 23].

Figure 8 shows a schematic of the proposed system. Because the direction of the field of view of the telescope is parallel to the direction of travel of the laser light, the time interval between the laser emission and signal acquisition is proportional to the distance between the receiving optics and the measuring point. The time interval between the laser emission and signal acquisition \( t_3 \) is

\[
t_3 = t_{\text{record}} - t_{\text{emit}},
\]

where \( t_{\text{record}} \) is the signal acquisition time, and \( t_{\text{emit}} \) is the laser emission time. The distance from the optics to the center of the measuring area \( R \) is

\[
R = \frac{ct_3}{2},
\]

where \( c \) is the speed of light. Figure 9 illustrates the relationship between \( t_3 \) and \( R \) and shows that the measurement point depends on \( t_3 \). The sampling frequency of sound at the measuring point equals the repetition frequency of the laser because the pulsed light passes the same point in each repetition period of the laser.

The received light power \( P \) is

\[
P(t_3) = \eta_{\text{L}} \int_{t_3/2}^{t_3+t/2} \int_{R_0} R_1 \frac{T(2r)}{r^2} \beta(\theta(r, y)) \, dy \, dr,
\]

where \( \eta_{\text{L}} \) is the cross section of the pulse light, and \( r \) is the pulse duration of the laser light. Because the cross section of the laser light is usually much smaller than that of the telescope, the integral term \( \eta_{\text{L}} \) can be regarded as constant.

When the pulse duration of the laser and \( \theta \) are small enough, Eq. (28) is rewritten as

\[
P(t_3) = \eta \eta_{\text{L}}(R) \frac{c \tau}{2} s_{\text{L}} s_{\text{T}} \frac{T(R)^2}{R^2} \beta(\tau),
\]

where \( s_{\text{T}} \) is the cross section of the telescope. When the scattered light from one point is detected with a fixed apparatus, the variables are the atmospheric transmissivity \( T \) and scattering coefficient \( \beta \). The term \( c \tau/2 \), which is the contribution of the pulse width to the scattering, is called the effective spatial pulse width. As noted above, \( T \) is regarded as constant, and the received power \( P \) is proportional to \( \beta \). Therefore, the sound pressure can be acquired from the intensity of scattered light.

5.2. Method

Figure 10 shows the experimental arrangement. Two speakers were placed 1 m from the laser light path and generated different sounds. The sound pressure at the points in front of each speaker was detected using backscattered light. The telescope, which had a field of view directed parallel to the direction of travel of the pulsed light, collected the scattered light. The scattered light was transduced to an electrical current by the PMT located at the focal point of the telescope. The PMT was mounted on a vibration isolation table. Optical filters that transmit only light with a wavelength nearly equal to that of the laser were used to suppress ambient light. A sample-and-hold circuit was used to extract the light scattered at a.

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![Diagram](image-url)
certain point. Because the sample-and-hold circuit can hold an instantaneous voltage value, the voltage value at a certain time after pulse emission was held by the circuit until the next pulse was received. The timing of the pulse emission and the clock for the sample-and-hold circuit were controlled by a function generator. The measurement points were determined by the phase difference of the clocks of the laser and the circuit, the interval of laser emission from trigger input, and the interval of signal acquisition of the circuit from trigger input. We made two measurements and set the measurement points 7.1 m and 16.3 m from the optics, respectively. The measurement points and the positions of the speakers did not agree because of a limitation of the configurable phase difference of the instruments. Speaker-1 was placed 8 m from the optics and generated a 1 kHz sine wave, and speaker-2 was placed 16 m from the optics and generated a 2 kHz sine wave. The sound pressure level of the sound generated by both speakers was 90 dB. As discussed in the Mie scattering experiment section, vibration of the optical system by the sound waves should be avoided. To ensure that the optics were not vibrated by the sound waves, the two sound sources were both 15 ms in duration, and the corresponding received signals were analyzed.

The specifications for the laser are shown in Table 2. An ultraviolet laser was used to increase the scattered light intensity because the intensity of Rayleigh scattering is inversely proportional to the fourth power of the wavelength of the incident light, as shown in Eq. (15). Since the pulse width of the light was 20 ns, the effective spatial pulse width was about 3 m. It means that the results include the integrated sound pressure along the pulsed light. Because the repetition frequency of the laser was 10 kHz, the upper limit frequency of the measurement was 5 kHz.

### Table 2: Specifications of the laser used for the experiment.

| Specification          | Value       |
|------------------------|-------------|
| Wavelength             | 355 nm      |
| Energy                 | 0.6 mJ      |
| Repetition frequency   | 10 kHz      |
| Pulse width            | 20 ns       |
| Beam diameter (at 10 m)| 1.4 mm      |

5.3. Results

The results are shown in Fig. 11. The power spectrum density and 95% confidence interval of the average of 200 signals are illustrated. The calculation conditions are shown in Table 3. Both figures show the values relative to the signals when the speakers generate no sound. Figure 11(a) indicates that the 1 kHz sine wave is detected when the measuring point is 7.1 m from the optics. According to Fig. 11(b), however, the 2 kHz sine wave was not captured. It seems that the 2 kHz signal is buried in noise because the intensity of the scattered light received at 16.3 m is 5.3 times less than that received at 7.1 m according to Eq. (29).

The experimental results suggest the possibility of acoustical measurement using air scattering, although the higher power laser is required, compared with measurement using tracers. This is because the scattering cross section of the air particles is much smaller than that of the water drops. It is necessary to improve the signal-to-noise ratio in order to apply this method to sound field measurements. To increase the laser power, increase the sensitivity.
of the PMT, reduce the loss of the optics and reduce the noise of the circuit are effective to improve the signal-to-noise ratio. In addition, to measure the sound pressure at a single point, a picosecond or shorter pulsed laser should be used.

6. CONCLUSION

In this paper, we proposed a sound measurement method using elastic light scattering and confirmed that the method enabled non-intrusive sound measurement. This method measures the sound pressure at an arbitrary point in free field without any disturbance to the sound field. Experiments using water drops and air particles as scatterers were conducted. Using water drops as scatterers increases the intensity of the scattered light because the scattering cross section of the water drops is much larger than that of air. Measurement using water drops is thus possible with a low-power light source. The experimental results indicate that sound measurement via light scattering is valid if the scattered light is sufficiently intense. When we used air particles as scatterers, the method is regarded as measuring the sound pressure directly. Because the scattering cross section of air is small, a powerful light source and highly sensitive photodetector are needed to observe the light scattered by air. In our experiment, the sound information 7.1 m from the optics was detected, but that at 16.3 m was not. It is expected that sound can be acquired with no addition by increasing the efficiency of the equipment and applying appropriate signal processing.

To establish this method as an absolute sound pressure measurement method, it is necessary to increase the signal-to-noise ratio, derive the absolute sound pressure level, and investigate the frequency characteristics and other properties. Moreover, when pulsed light backscattered by air particles is observed, the detected signal contains spatially continuous acoustical information. Therefore, this method has the potential to measure the spatial behavior of the sound field directly, which is difficult using typical microphones. The method is expected to be applied to spatial sound field measurement.

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APPENDIX: DERIVATION OF EQ. (24)

Figure A·1 illustrates the system when the sound presents (a) nowhere along the optical path, (b) at the
Both the extinction coefficient and the scattering coefficient change by the sound. Therefore,
\[
T_b = e^{-2R_{0a}}, \quad \beta_b = \beta_0 + \Delta \beta, \quad P_b = \frac{P_{in}}{R^2} e^{-2R_{0a}(\beta_0 + \Delta \beta)},
\]
where \(\Delta \beta\) is the variation of the scattering coefficient caused by the sound.

(c) When the sound presents on a unit length of the optical path except the scattering point, the extinction coefficient is different in the regions where the sound presents and not. Since the sound presents on the unit length of the optical path, the atmospheric transmissivity is given by
\[
T_c = e^{-(2R-1)\alpha_0 + \Delta \alpha_0)},
\]
where \(\Delta \alpha\) is the variation of the extinction coefficient caused by the sound. Since the absorption of the transmitted light by air is small, the variation in the absorption coefficient can be regarded as zero. Therefore, \(\Delta \alpha\) is equals to \(\Delta \beta\). The scattering coefficient is the static value because there is no sound at the scattering point. Thus, the received light power is
\[
P_c = \frac{P_{in}}{R^2} e^{-2R_{0a}} e^{-\Delta \beta \beta_0}. \quad (A-9)
\]

The ratio of the variation caused by sound at the scattering point and on the optical path, \(P_{ratio}\), is
\[
P_{ratio} = \frac{P_b - P_a}{P_c - P_a}. \quad (A-10)
\]
Substituting Eqs. (A-4), (A-7), and (A-9) into Eq. (A-10), the ratio becomes
\[
P_{ratio} = \frac{\Delta \beta}{(e^{-\Delta \beta} - 1)\beta_0}. \quad (A-11)
\]
According to Eqs. (16), (17), and (18), the scattering coefficient is
\[
\beta = \frac{\rho_0}{M} \left(1 + \gamma \frac{p}{p_0} \right) \frac{d\sigma(\theta)}{d\Omega}. \quad (A-12)
\]
Thus, \(\beta_0\) and \(\Delta \beta\) are
\[
\beta_0 = \frac{\rho_0}{M} \frac{d\sigma(\theta)}{d\Omega}, \quad \Delta \beta = \frac{\rho_0}{M} \gamma \frac{p}{p_0} \frac{d\sigma(\theta)}{d\Omega} = \gamma \frac{p}{p_0} \beta_0, \quad (A-13)
\]
respectively. Substituting Eqs. (A-13) and (A-14) into Eq. (A-11) yields the ratio given by Eq. (24).
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