2. Theory

Sound wave is a mechanical wave propagating in an elastic medium with sound speed as the basic physical quantity to describe the acoustic propagation characteristics in the medium. In air, wave phenomena can be demonstrated not only with visible light and microwaves, but also with sound waves. Unlike electromagnetic waves, sound waves are however longitudinal rather than transverse waves. Hence, sound waves are never polarized.

Since ultrasound waves are directional and anti-jamming, it is often to use ultrasound waves to measure sound speed. Using this apparatus, a series of experiments such as sound speed measurement using resonance interference and phase comparison methods, and double-slit interference/single slit diffraction/reflection of sound waves can be conducted to understand basic physics laws and concepts of waves.

1) Resonance interference method

If a plane sound wave at a certain frequency emitted from a sonic source arrives at a receiver in air and the surfaces of the emitter and the receiver are strictly parallel, the incident wave will be reflected by the receiver forming a standing wave. The wave node is on the reflection plane. At certain distances between the receiver and the emitter, stable standing wave resonance can occur. If the distance equals an integer of the half wavelength of the sound wave, the amplitude of the standing wave reaches maximum. Under this condition, the sonic pressure on the surface of the receiver also reaches a peak value. Obviously, the displacement of the receiver between adjacent maximum resonance peaks is a half of the wavelength of the sound wave. Therefore, if the frequency of the sound wave, ν, is known and remains unchanged, the speed of sound in air can be calculated using formula $V=\nu\lambda$.

2) Phase comparison method

Apparently, the phases of sound wave at the receiver and the emitter are different with a phase delay, φ, which can be observed from the Lissajous graph on an oscilloscope. Also, we have

$$\varphi = \omega t \tag{1}$$

where ω is the angular frequency of the sound wave, and t is the traveling time. Also $\omega=2\pi/T$, $t=l/\mathrm{V}$, and $\lambda=T\mathrm{V}$ (T is the period). Thus, we get

$$\varphi = 2\pi\ l/\lambda \tag{2}$$

When $l=n\lambda/2$ (n=1, 2, 3, …), we have $\varphi=n\pi$.

In this experiment, by changing the distance between emitter and receiver, phase change can be observed. When the phase difference reaches π, the corresponding change in distance is a half of the wavelength. So, the speed of sound can be calculated.

3) Speed of sound in ideal gas

The propagation of a sound wave in ideal gas can be considered as an adiabatic process, so the propagation speed can be written as:

$$\mathrm{V} = \sqrt{\frac{rR\Theta}{\mu}} \tag{3}$$

where R is a constant (R=8.314 J·mol^{-1}·K^{-1}), γ is the heat capacity ratio of the gas at constant pressure and at constant volume (adiabatic index of the gas), μ is the molecular weight of the gas, and Θ is the thermodynamic temperature of the gas. If the temperature of the gas is θ in Celsius, we have: $\Theta=\Theta_0+\theta$ (Θ_0=273.15 K). Now, Eq. (3) can be rewritten as:

$$V=\sqrt{\frac{rR}{\mu}(\Theta_0+\theta)}=\sqrt{\frac{rR}{\mu}\Theta_0}\cdot\sqrt{1+\frac{\theta}{\Theta_0}}=V_0\sqrt{1+\frac{\theta}{\Theta_0}} \tag{4}$$

In air, the speed of sound at 0 °C is 331.45 m/s. By considering the vapor effect in air, the formula of sound speed after calibration is:

$$V=331.45\sqrt{(1+\frac{\theta}{\Theta_0})(1+\frac{0.319p_w}{p})} \tag{5}$$

where p_w is the partial pressure of vapor, and p is the atmospheric pressure.

4) Interference, diffraction, and reflection of sound wave

As shown in Figure 1, at a specific receiving angle a, if the path difference of the two waves transmitted from the two slits to the receiver is zero or an integer of the wavelength, constructive interference occurs leading to a maximum interference intensity detected by the receiver; when the path difference is an odd integer of one half of the wavelength, destructive interference intensity occurs resulting in a minimum interference intensity.

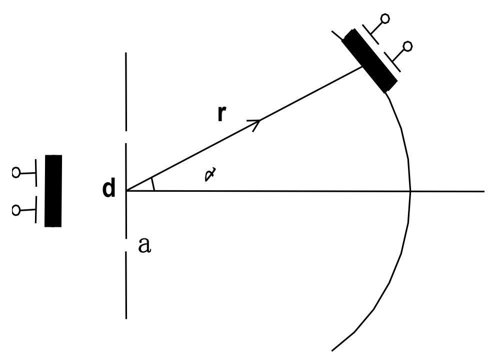

Figure 1 Schematic of double slit interference of sound wave

Thus, the conditions for maximum and minimum interference are:

$$\text{Maximum: } d\sin\alpha=n\lambda \tag{6}$$

$$\text{Minimum: } d\sin\alpha=(n+\frac{1}{2})\lambda \tag{7}$$

where n is zero or an integer, d is the distance between the centers of the two slits, and λ is the wavelength of the sound wave.

Similarly, a setup using a device called Lloyd mirror can create a virtual image of the emitting source as shown in Figure 2. Here, the interference pattern is generated by the direct wave and the reflected wave.

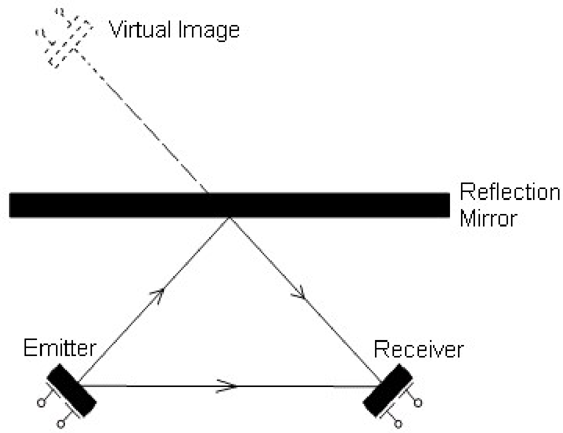

Figure 2 Interference of sound wave by Lloyd mirror

The diffraction of a sound wave by a single slit can also be observed, as shown in Figure 3. When the radiation from one half of the single slit interferes with that from the other half of the single slit, a destructive interference occurs if their paths differ by an odd integer of one half of the wavelength, as:

$$\frac{d}{2}\sin\alpha = (n+\frac{1}{2})\lambda \tag{8}$$

where n=0, ± 1, ± 2,......, d is the width of the single slit, and α is the angle of the receiver relative to the central axis perpendicular to the slit.

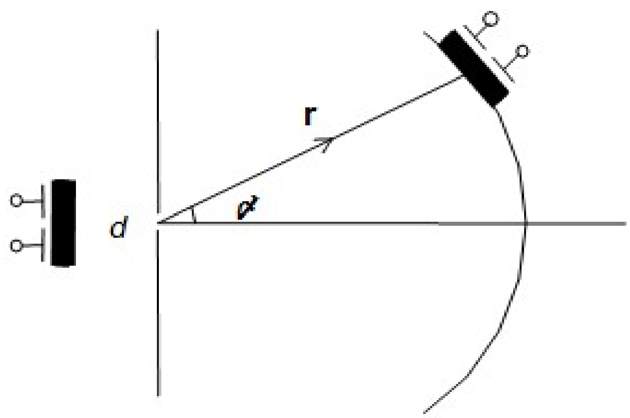

Figure 3 Diffraction of sound wave by single slit