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 can be conducted such as sound speed measurement using resonance interference and phase comparison methods, and measurement of distance using an ultrasonic wave.

1) Measurement of sound speed using 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 l equals an integer of the half wavelength ($\lambda/2$) 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) Measurement of sound speed using 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 $\omega=2\pi/T$, $t=l/V$, and $\lambda=TV$ (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) Measurement of sound speed using time difference method

The time difference method for measuring the sound speed is a commonly used method in engineering. A pulse-modulated sinusoidal signal is input to the ultrasonic transmitter to generate a pulsed ultrasonic wave. It reaches the ultrasonic receiver at a distance L after time t. The sound speed can be directly calculated according to the following formula:

$$V = \frac{L}{t}. \tag{3}$$

4) Ultrasonic ranging

The principle of ultrasonic distance measurement using reflection method is based on the propagation speed of ultrasonic wave in the air is known. By measuring the time difference between the sound wave emitting and the sound wave reflected back from the interested object, the distance from the instrument to the object can be calculated. The principle is the same as that of radar. The measurement formula is follows:

$$L = VT/2, \tag{4}$$

where L is the measured distance, V is the propagation speed of the ultrasonic wave in the air; and T is the time difference between the time of transmission and reception.

5) 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:

$$\mathrm{V} = \sqrt{\frac{rR\Theta}{\mu}} \tag{5}$$

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. (5) can be rewritten as:

$$\mathrm{V} = \sqrt{\frac{rR}{\mu}(\Theta_0+\theta)} = \sqrt{\frac{rR}{\mu}\Theta_0} \cdot \sqrt{1+\frac{\theta}{\Theta_0}} = \mathrm{V}_0\sqrt{1+\frac{\theta}{\Theta_0}} \tag{6}$$

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:

$$\mathrm{V} = 331.45\sqrt{(1+\frac{\theta}{\Theta_0})(1+\frac{0.319p_w}{p})} \tag{7}$$

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