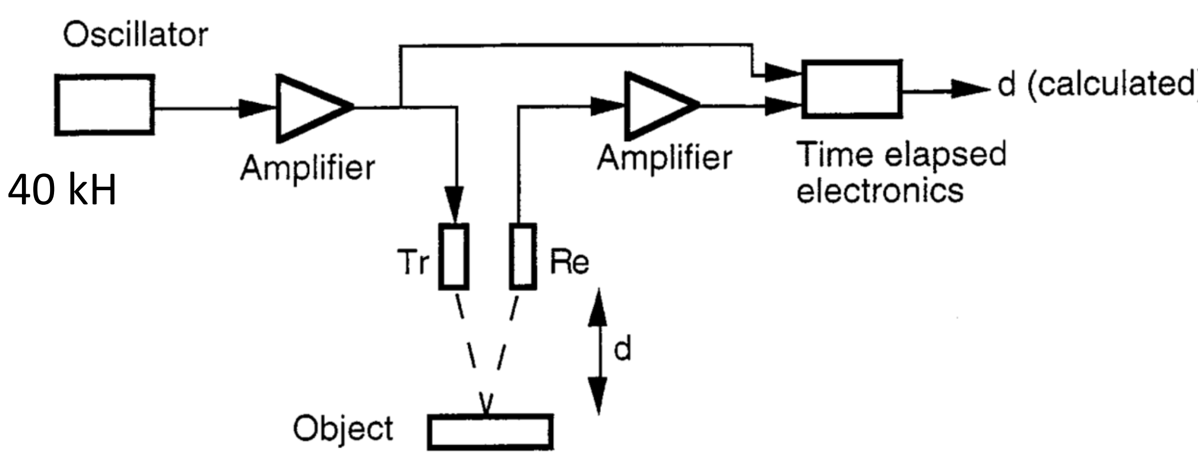
Ultrasonic and its applications

(measurement of flow, displacement and non-destructive testing)

- Ultrasound is an acoustic wave with a frequency higher than the audible range of the human ear, which is 20 kHz.
- Ultrasound can be within the audible range for some animals, like dogs, bats, or dolphins.
- In the years around 1883, Sir Francis Galton performed the first known experiments with whistles generating ultrasound.
- Many decades later, people started to find ultrasound applications in engineering, medicine, and daily life.
- The basic principle for the use of ultrasound as a measurement tool is the *time-of-flight technique*.

- The pulse-echo method is one example. In the pulse-echo method, a pulse of ultrasound is transmitted in a medium. When the pulse reaches an another medium, it is totally or partially reflected, and the elapsed time from emission to detection of the reflected pulse is measured.
- This time depends on the distance and the velocity of the sound. When sound travels with a known velocity *c*, the time *t* elapsed between the outgoing signal and its incoming echo is a measure of the distance *d* to the object causing the echo.

$$d=ct/2$$



- ✓ For precise measurements, the speed of sound is a crucial parameter.
- ✓ A typical value in air at 1 atm pressure and room temperature is 343 m s^{-1}, but the speed of sound is influenced by air pressure, air temperature, and the chemical composition of air (water, CO2, etc.).
- ✓ For example, the speed of sound is proportional to the square root of absolute temperature.
- ✓ Measuring distances in an environment with large temperature gradients can result in erroneously calculated distances.
- ✓ As an advantage, ultrasound waves are robust against other disturbances such as light, smoke, and electromagnetic interference

Physical Characteristics of Sound Waves

- Sound is a vibration in matter. It propagates as a longitudinal wave, i.e., the displacement in the material is in the direction of the sound wave propagation. A plane wave that propagates in the *x* direction can be described by

$$\Delta x = A \sin \omega \left(t - \frac{x}{c} \right)$$

- where A is the amplitude, $\omega = 2\pi f$, f being the frequency of the wave and Δx is the displacement of a particle at time *t* at the position *x*.
- The velocity of sound depends on the medium in which it propagates. In a homogeneous and isotropic solid, the velocity depends on the density ρ and the modulus of elasticity E

$$c = \sqrt{\frac{E}{\rho}}$$

Physical Characteristics of Sound Waves

- In a liquid, the velocity depends on the density and the adiabatic compressibility K

$$c = \sqrt{\frac{1}{K\rho}}$$

- In gases, the velocity of sound is described by Equation (shown below). Here g represents the ratio of the specific heat at constant pressure (cp) to the specific heat at constant volume (cv), p is pressure, R is the universal gas constant, T is the absolute temperature, and M is the molecular weight.

$$c = \sqrt{\frac{gRT}{M}} = \sqrt{\frac{c_p}{c_v}\frac{p}{\rho}}$$

Physical Characteristics of Sound Waves

- An important quantity is the specific **acoustic impedance**. It is, in general, a complex quantity but in the far field (Figure), the imaginary component disappears, leaving a real quantity. This real quantity is the product of the density ρ and the sound speed c in the medium. This product is called the characteristic impedance R_a

$$R_a = \rho c$$

The characteristic impedance is thus independent of the sound frequency.

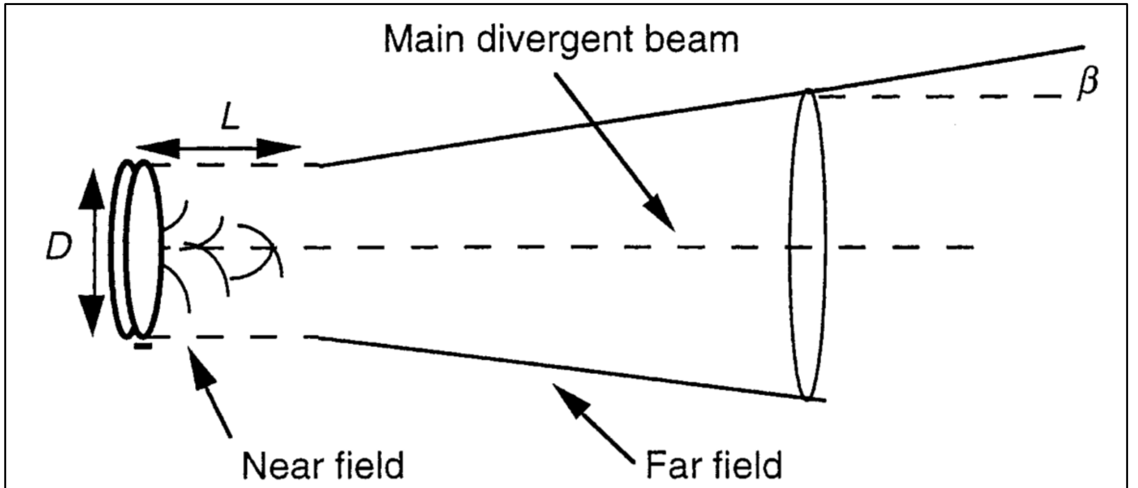


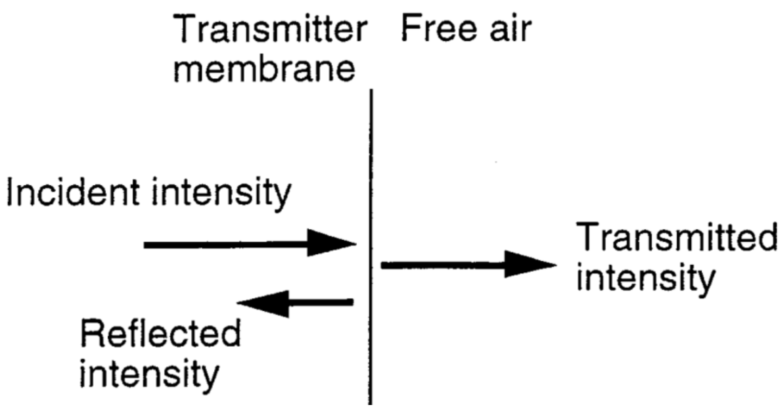
Fig. Illustration of the ultrasound beam in the near field and the far field of the transducer.

Physical Characteristics of Sound Waves

- An acoustic wave has an intensity *I* (rate of flow of energy per unit area), which can be expressed in watts per square meter (W/ m–2).
- A usually unwanted phenomenon arises when the sound wave has to pass from one medium with characteristic impedance R_1 to another medium with characteristic impedance R_2.
- If R_1 and R_2 have different values, a part of the wave intensity will reflect at the boundary between the two media (shown in Figure). The two media are said to be mismatched, or poorly coupled, if a major part of the wave intensity is reflected and a minor part is transmitted. The relative amounts of reflected and transmitted wave intensities can be defined by:

$$\text{Reflection coefficient} = \frac{I_{\text{refl}}}{I_{\text{incident}}}$$

$$\text{Transmission coefficient} = \frac{I_{\text{trans}}}{I_{\text{incident}}}$$



$$\text{Reflection coefficient} = \frac{\left(R_1 - R_2\right)^2}{\left(R_1 + R_2\right)^2}$$

$$\text{Transmission coefficient} = \frac{4R_1R_2}{\left(R_1 + R_2\right)^2}$$

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Most ultrasound transducers convert electric energy to mechanical energy and vice versa. The most common types of in-air transducers are

- **1. Mechanical**
- **2. Electromagnetic**
- **3. Piezoelectric**
- **4. Electrostatic**
- **5. Magnetostrictive**

- The simplest type, **mechanical transducers** such as whistles and sirens, are used up to approximately 50 kHz. This type works only as a transmitter.

- **Electromagnetic transducers** such as loudspeakers and microphones can be used for ultrasonic wave generation, but they are mainly suited for lower frequencies.

- **The piezoelectric transducer** is more suitable for use in ultrasonic and is quite common. It uses a property of piezoelectric crystals: they change dimensions when they are exposed to an electric field. When an alternating voltage is applied over the piezoelectric material, it changes its dimensions with the frequency of the voltage. The transducer is mainly suited for use at frequencies near the mechanical resonance frequency of the crystal. The piezoelectric transducer can be both a transmitter and a receiver: when a piezoelectric material is forced to vibrate by a sound pulse, it generates a voltage.
- **The electrostatic transducer** is a plate capacitor with one plate fixed and the other free to vibrate as a membrane. When a voltage is applied between the plates, the electrostatic forces tend to attract or repel the plates relative to each other depending on the polarity of the voltage. This transducer can be used both as a transmitter and a receiver.

- **The magnetostrictive transducer** is based on the phenomenon of magnetostriction, which means that the dimensions of a ferromagnetic rod change due to the changes of an externally applied magnetic field. This transducer can also act as both a receiver and a transmitter.

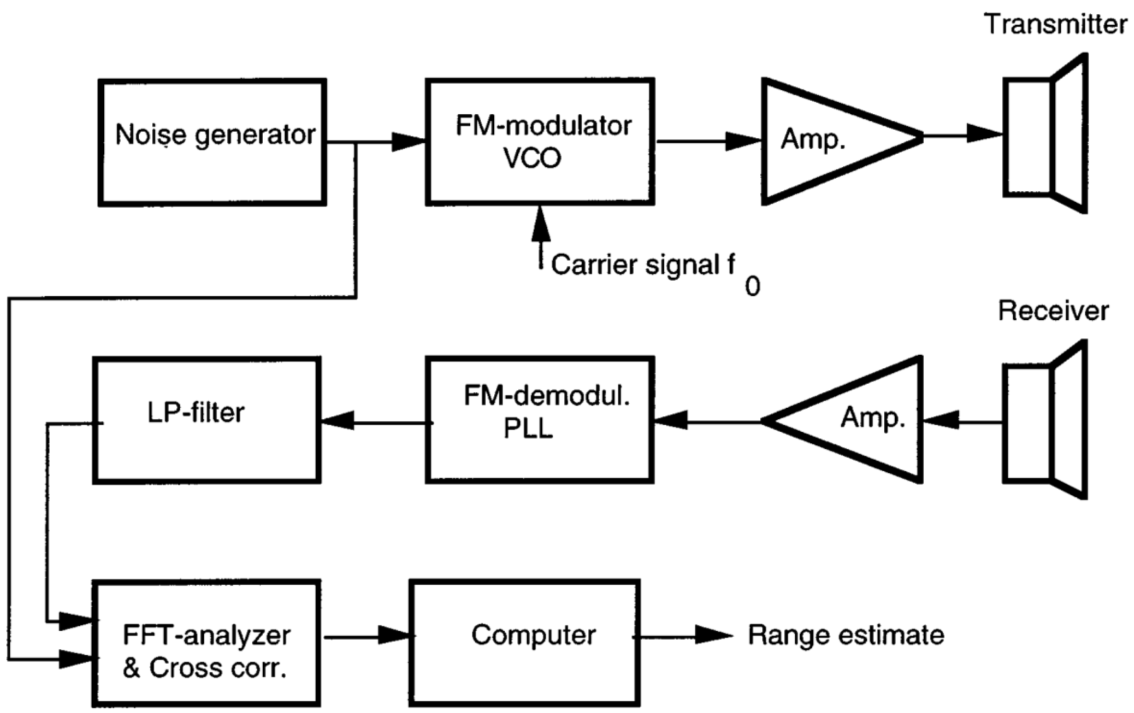
Principles of Time-of-Flight Systems

There are several techniques for ultrasonic range measurements.

- The previously described **pulse echo method** is the simplest one. Usually, this method has a low signal to-noise ratio (SNR) because of the low transmitted energy due to the short duration of the pulse. Multi-reflections are also detectable.
- In the **phase angle method**, the phase angle is measured between the continuous transmitted signal and the continuous received signal and is used as a measure of the distance. The method is relatively insensitive to disturbances. Multi-reflections are not detectable in a meaningful way. When the distance is longer than one wavelength, another method must be used to monitor the distance. The frequency modulation method uses transmitted signals that are linearly frequency modulated. Thus, detected signals are a delayed replica of the transmitted signal at an earlier frequency. The frequency shift is proportional to the time-of-flight. The method is robust against disturbing signals, and multireflections are detectable.

Principles of Time-of-Flight Systems

- The **correlation method** (Shown in Figure) determines the cross-correlation function between transmitted and received signals. When the transmitted signal is a random sequence, i.e., white Gaussian noise, the cross-correlation function estimates the impulse response of the system, which, in turn, is a good indicator of all possible time delays. The method is robust against disturbances, and multire-flections are detectable



Advantages and Disadvantages of Time-of-Flight Methods

Method	Main advantage	Main disadvantage
Pulse echo method	Simple	Low signal-to-noise ratio
Phase angle method	Rather insensitive to disturbances	Cannot be used directly at distances longer than the wavelength of the ultrasound
Frequency modulation method	Robust against disturbances; multireflections detectable	Can give ambigous results measurements on long and short distances can give the same result (compare with phase angle method)
Correlation method	Very robust against disturbances	Make relatively high demands on hardware and/or computations

Ultrasonic Flow Meters

Pressure variations travel through a fluid at the velocity of sound relative to the fluid.

If fluid is in motion with certain velocity, then the absolute velocity of pressure disturbance propagation is the algebraic sum of the two.

“The term ‘ultrasonic’ refers to the pressure differences (usually are short bursts of sine waves) whose frequency is above the range audible to human hearing which is 20 to 20000 Hz”

Principle: “**The ultrasonic flow meter operates on the principle that the velocity of sound in a fluid in motion is the resultant of the velocity of sound in the fluid at rest plus or minus the velocity of the fluid itself**”

Types of Ultrasonic Flow Meters

(i) Transit time flow meters

(ii) Doppler Flow meter.

Transit Time Flow Meters

As the name implies, these devices measure flow by measuring the time taken for an ultrasonic energy pulse to traverse a pipe section, both with and against the flow of the liquid within the pipe. Figure shows a representative transit time flow meter

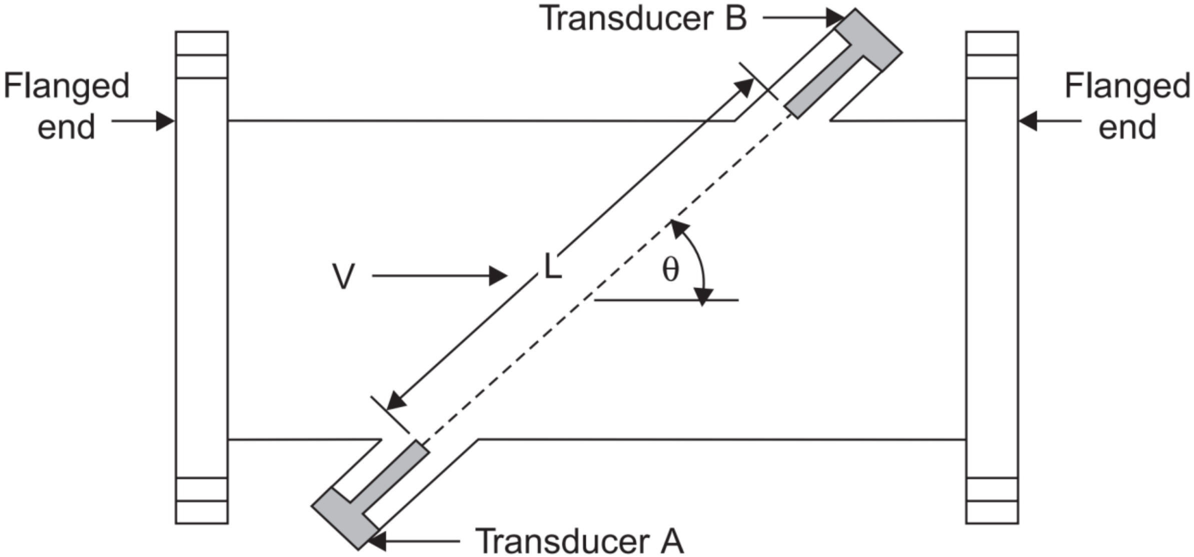


Fig. Transit-time flow meter

The time (t_{AB}) for the ultrasonic energy to go from transducer A to transducer B is given by the expression :

$$t_{AB} = L/(C + V.\cos\theta)$$

The time (t_{BA}) to go from B to A is given by

$$t_{BA} = L/(C - V.\cos\theta)$$

where C is the speed of sound in the fluid

L is the acoustic path length in the fluid

and θ is the angle of the path with respect to the pipe axis.

By combining and simplifying, it can be shown that for V << C :

$$\Delta t = t_{BA} - t_{AB} = 2.L.V.\cos\theta/C^2$$

It can be shown that :

$$V = L.\Delta t/2\cos\theta\, t_A^2 = K\,\Delta t/t_A^2$$

where t_A is the average transit time between the transducers.

Since the cross sectional area of the pipe section or 'spool pipe' is known, the product of area and velocity will yield the volumetric flow rate.

Frequency Difference-Type

In this type, the reciprocals of transit times are used. This leads to a frequency difference (Δf) which is proportional to the flow velocity V. The difference in frequencies is related to the velocity as follows :

$$V = \Delta f.L/2. \cos \theta$$

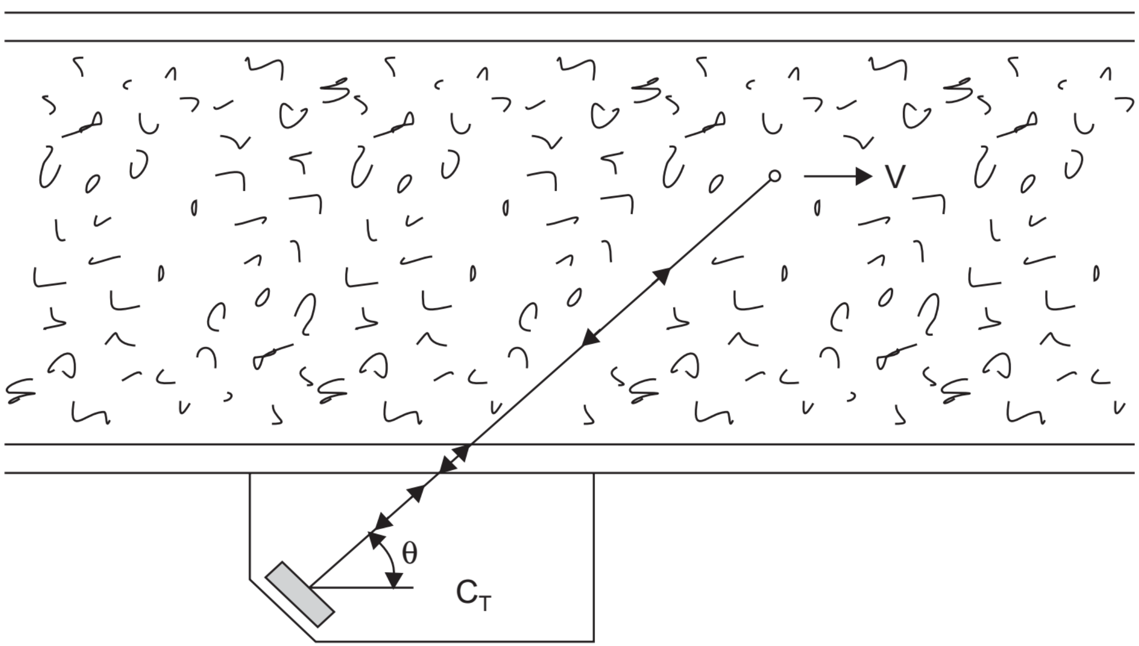
The multipulse time shift reflection method uses one or more pulses and times them to determine the change in range per second to an ensemble of scatters. The change in range per unit time yields the velocity of scatters.

Doppler Flow Meters

This type of flow meter is based on Doppler principle. The transmitter of a Doppler flow meter projects an ultrasonic beam at a frequency of about 0.5 MHz into the flowing stream and deflects the reflected frequency. The difference between transmitted and reflected velocities is called the ‘beat frequency’ and is related to the velocity of the reflecting surfaces (solid particles and gas bubbles) in the process stream.

Doppler Flow Meters

- As shown in Fig. 9, an ultrasonic wave is projected at an angle through the pipe wall into the liquid by a transmitting crystal in a transducer mounted outside the pipe.
- Part of the energy is reflected by bubbles or particles in the liquid and is returned through the pipe wall to a receiving crystal.
- If the reflectors are travelling at the fluid velocity, the frequency of the reflected wave is shifted according to the Doppler principle, in proportion to the flow velocity



Doppler Flow meter Principle of operation