

ECHOLOCATION BY ULTRASOUND

Introduction

Ultrasound refers to sound above the human audible limit of 20 kHz. Ultrasound of frequencies up to 10 MHz and beyond is used in medical diagnosis, therapy and surgery. In investigative applications, an ultrasound source (transmitter) directs pulses into the body. When the pulse encounters a boundary between organs or between two tissue regions of different densities, reflections of sound occur. By scanning the body with ultrasound and detecting echoes generated by various organs, a sonogram of the internal structure(s) can be generated. The method is called **diagnostic imaging by echolocation**. A static sonogram can be recorded for a fixed internal structure, but in the case of moving objects (red blood cells moving in arteries) or an oscillating organ (the heart), the method uses the **Doppler shift** of the echo frequency with respect to the transmitted one. Typical is the echocardiogram, in which a moving image of the heart is produced in video form to indicate the speed and direction of blood flow and heart valve movements.

The Doppler effect

Whenever a sound source is moving toward or away from an observer, the perceived frequency will be different than the actual frequency emitted by the source when stationary.

The explanation of motion-related frequency changes was proposed in 1842 by Christian Doppler and was experimentally tested in 1845 in Holland, by using *a locomotive drawing an open car with several trumpeters*. We shall examine two of the Doppler situations:

1) A detector moves at speed v_D towards a stationary source of sound. As it moves into the waves, it will intercept more wavefronts and thus the frequency f' received by the detector can be expressed as:

$$f' = \frac{c + v_D}{\lambda} = f \frac{c + v_D}{c} = f \left(1 + \frac{v_D}{c}\right) \quad (1)$$

We assumed that the stationary source emits frequency $f = \frac{c}{\lambda}$, where c is speed of sound, λ is the sound wavelength.

The Doppler shift is defined as: $\Delta f = f' - f = f \frac{v_D}{c}$ (1')

2) The detector is stationary and the sound source moves toward it at speed v_S . The motion of the source changes the emitted wavelength: ahead of the source, wavelength is shorter: $\lambda' < \lambda$. The frequency received by detector can be expressed as:

$$f' = \frac{c}{\lambda'} = f \frac{c}{c - v_S} \quad (2)$$

The Doppler shift will be defined as: $\Delta f = f' - f = f \frac{v_S}{c - v_S}$ (2')

A Flash animation on the Doppler Effect can be found at:

<http://faraday.physics.utoronto.ca/PVB/Harrison/Flash/ClassMechanics/Doppler/DopplerEffect.html>

Echolocation of a moving object

A stationary ultrasound source of frequency f , a moving object R and an ultrasound receiver detector are arranged as shown in Figure 1.

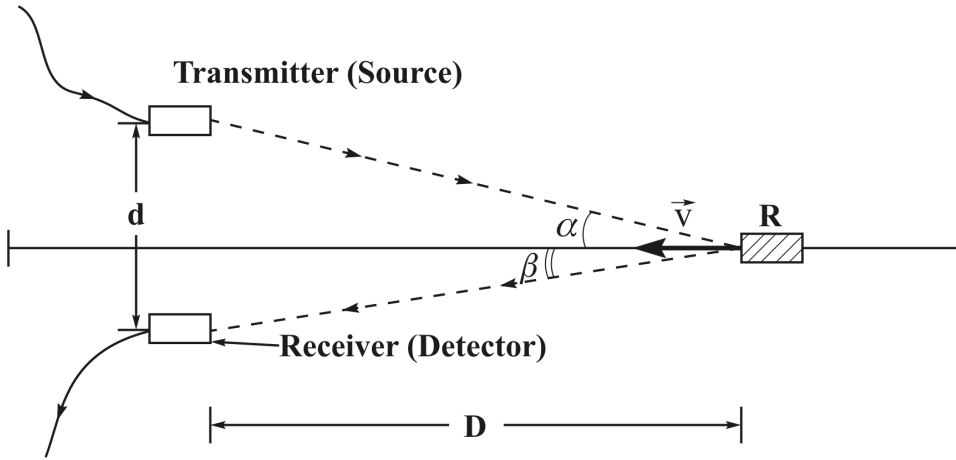


Figure 1. Echolocation of a moving object

As it moves at a constant speed, the object intercepts the ultrasound and scatters it back. The frequency received by the moving object is expressed as:

$$f' = \frac{c + v_o \cos \alpha}{v_s} f \quad (3)$$

(The velocity of the object towards the source is $v_o \cos \alpha$).

As it scatters ultrasound, the object becomes a secondary, moving ultrasound source. The velocity of this source towards receiver is $v_o \cos \beta$.

The receiver measures a frequency f'' which can be written as:

$$f'' = \frac{c}{c - v_o \cos \beta} f' = \frac{c}{c - v_o \cos \beta} \frac{c + v_o \cos \alpha}{c} f \quad (4)$$

If the experimental arrangement is symmetric ($\alpha \simeq \beta$) and if we assume: $v_o \cos \alpha \ll c$, the Doppler shift can be written as:

$$\Delta f = f'' - f \simeq \frac{2v_o \cos \alpha}{c} f \quad (5)$$

Experimentally, we can measure the *beat frequency* between the transmitted (f) and received (f'') sounds, amplified as *Doppler waveform*, from which we obtain the Doppler shift.

Knowing the ultrasound frequency f and speed c , we can measure the Doppler shift Δf and the angle α and thus we can calculate the speed of the moving object v_o :

$$v_o = \frac{c \Delta f}{2f \cos \alpha} \quad (5')$$

The arterial ultrasound scan

In the arterial ultrasound scan, the ultrasound beam is oriented as parallel as possible to the direction of the blood flow ($\cos\alpha \simeq 1$) in order to maximize the Doppler shift reading (Eq. 5).

Blood consists of a clear liquid (plasma), red blood cells (erythrocytes), platelets and leukocytes. Erythrocytes are the most numerous and also have the right size to scatter the ultrasound. As they travel with the blood, they will have different individual velocities and thus will scatter the ultrasound as multiple frequencies. At any time during the systolic activity, there is a range of Doppler shift frequencies, which are converted to velocities and displayed as a *velocity spectrum* of the blood flow.

The increase in blood speed as a result of a constriction or obstruction of an artery is measured as an increase of the peak velocity in the velocity spectrum.

Echolocation of an oscillating object

An object moving in a low frequency oscillation scatters back the ultrasound wave, but the receiver detects the superposition of the low frequency oscillation and the scattered frequency. With an appropriate filtering of this signal, the Doppler waveform corresponding to the uniform back and forth travel of the reflecting object can be measured.

The heart valve is an example, with a typical frequency of 75 beats/min or 1.25 Hz. If we consider an experimental setup with the transmitter and receiver arranged to send/receive ultrasound at $\alpha = 0^\circ$, we can use a simplified Doppler shift expression to analyze the waveform:

$$\Delta f \cong \frac{2v_o}{c} f \quad \text{where } v \text{ is the speed of sound, } f \text{ is the transmitter frequency.}$$

This would enable us to calculate the speed (v_o) of the oscillating object:

$$v_o = \frac{c \Delta f}{2f}$$

The experiment

There are two parts of this experiment:

1. You'll investigate how to echolocate a moving object and examine the elements which determine the Doppler shift frequency;
2. An oscillating object will be studied, with the purpose of indirectly measuring its speed.

1. Echolocation of a moving object

1.1 Setup

Figure 2 presents the block diagram of the echolocation setup.

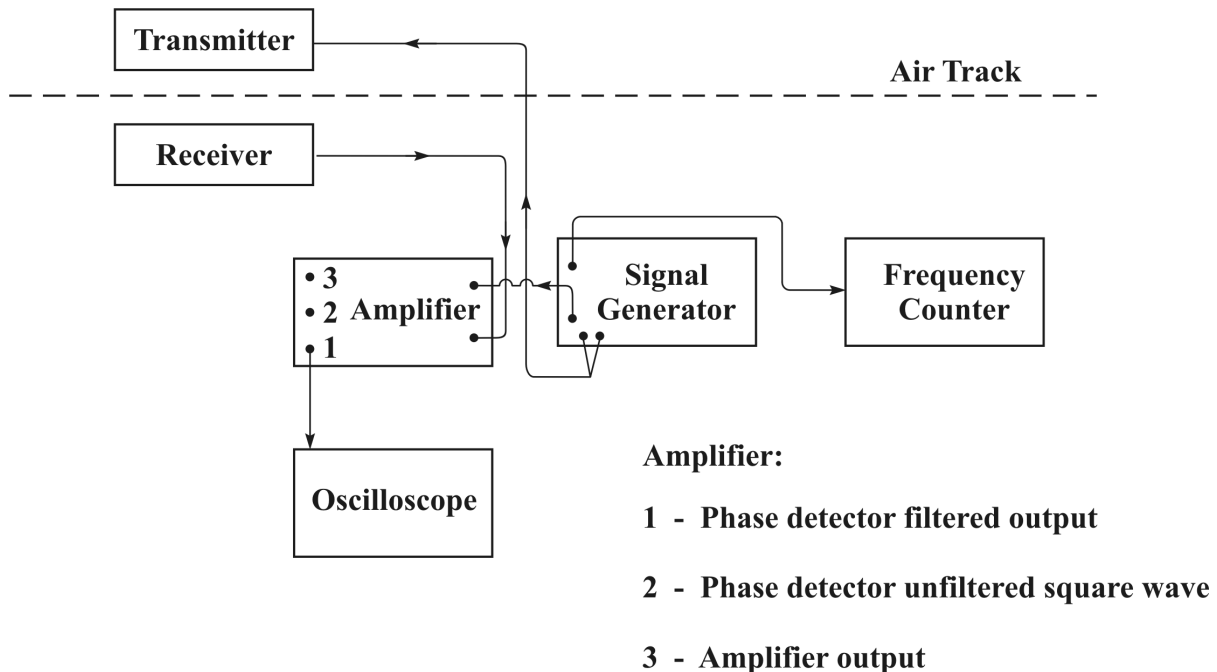


Figure 2. The echolocation setup

An air track with an electronic launcher, a set of two coupled photogates and a glider with a perforated reflector are also used.

The transmitter and receiver can be rotated around the holders' vertical axis. The laser pointer attached to each holder allows a better alignment of the sent/received ultrasound directions.

The transmitter frequency ($f \approx 43$ kHz) is intercepted by the moving glider's reflector and scattered back to the receiver. The *beat frequency* between the transmitted and the received frequencies is amplified and low pass filtered. The oscilloscope displays the Doppler waveform: a sinusoidal form with frequency Δf (see Eq. 5).

The oscilloscope is a digital, real time storage instrument. While doing your experiment, you will be using a number of the main oscilloscope functions, so it may be useful if you consulted the Tektronix reference: www.tek.com/Masurement/App_Notes/XYZs/ before coming to the lab. If you have never used an oscilloscope, you may also check the web documents from:

<http://www.upscale.utoronto.ca/PVB/Harrison/Flash/index.html#scope>

The oscilloscope controls can be divided into three groups:

- Controls for the vertical (y) motion of the beam: vertical position, vertical sensitivity, CH 1 \leftrightarrow CH 2 beam selection **DC-AC-Ground** input coupling switches;
- Controls for the horizontal (x) motion of the beam: horizontal sweep speed, horizontal position, x sensitivity (when the oscilloscope is in the x-y mode);
- Controls of the time base circuits, which internally feed the x deflection of the beam

(trigger controls).

Each of the main buttons calls up a menu on the right of the screen and the buttons beside the menu allow you to select various functions.

The oscilloscope measures the voltage between the central wire of the coaxial input cable and the grounded outer wire braid. You will be using one or two inputs (CH 1, CH 2) of the oscilloscope and will have one/two traces on the screen.

In observing the Doppler effect, the moving object has to be measured every time at the same position (the red arrow mark on the track)

1.2 Doing the experiment

Connect the instruments as in Figure 2. The oscilloscope should be connected to the filtered output of the amplifier.

Fully turn on the air blower and check the level of the air track.

Arrange the transmitter and receiver at a distance of ~ 8 cm from each other, with the midpoint right above the track. Check if the glider reflector can slide freely between them. Hold the reflector at the arrow mark on the track, turn on the laser pointers (pull them back in their holders) and slowly rotate the transmitter until the laser spot can be seen on the reflector. Do the same alignment with the receiver.

Arrange one photogate at the arrow mark, check if the reflector slides freely. Set the photogate on GATE (it will measure the time of passage of the reflector through it). Set up the glider launcher at 15V. Launch the glider/reflector to check if it has a free passage through the setup components.

Oscilloscope: VOLTS/DIV of each channel are displayed at the bottom (left) of the screen. The TRIGGER source and level (in mV) are displayed at the bottom (right) of the display.

CH1 menu: Coupling=DC, BW Limit=ON (20 MHz), VOLTS/DIV=1V/cm

TRIGGER menu: Source=CH1, Mode=Auto, Coupling=DC, LEVEL=make it positive

HORIZONTAL: SEC/DIV=2.5ms/cm

Launch the glider and, as it passes through the arrow mark point, press RUN/STOP (on the right upper corner of the oscilloscope). This will freeze the display, so you can read the Doppler waveform frequency. To unfreeze it, press the same button again. Practice until you can synchronize the passage of glider with your stopping of the oscilloscope. Press MEASURE to read the Doppler shift frequency.

Read the ultrasound frequency (f) from the frequency counter. Read the photogate time Δt .

Take at least 5 readings of the Doppler shift frequency Δf , calculate the average value. Vary the launching voltage up to 22V. Measure the average Doppler shift frequency Δf , for each launching speed (5-6 values).

The glider speed v_0 can be calculated, knowing the length of the reflector, as it is seen by the photogate, and also the time it travels through the gate (Δt).

From Figure 1, we can calculate the angle α , knowing the distance d between the transmitter and receiver, and also the distance D between the arrow mark and the transmitter/receiver heads ($\cos\alpha \simeq 0.99$ for $d \simeq 8$ cm and $D \simeq 40$ cm)

Using the simplified equation 5: $\Delta f \cong \frac{2v_0}{c} f$, you can plot Δf versus v_0 (see Correction for speed, below). From the slope, you may get the value of the speed of sound in air (c).

Correcting the speed value. As you probably noticed, the reflector we use in this experiment has been perforated to reduce the air resistance. However, we couldn't

eliminate the resistance, so the glider speed along the track is not constant. Using the two photogates, design a method to evaluate the correction we need to apply to the glider speed. Correct the values before you do the first graph.

The angle correction. Equation 5 shows that the Doppler shift depends on the angle between the direction of ultrasound and the direction of object motion. You have to check how important this dependency is.

Setup the launcher voltage at 15V and measure the Doppler shift for different distances d (transmitter to receiver, see Figure 1), between 8 and 30 cm. Every time you change d , you have to re-align the direction of the transmitted and received ultrasound. For each distance d , measure the average Doppler shift frequency.

In medical use of Doppler echo methods, the American Society of Echocardiography recommends a maximum relative error of 6% in blood flow velocity measurements¹, due to the angle inclusion in equation (5). Which is the maximum value α_{\max} of the angle that corresponds to this relative error of glider velocity in our experiment?

Verify the complete form of Eq.(5) by plotting Δf versus $\cos\alpha$. From the slope, calculate the glider speed. Compare it with a direct measurement, using the photogate at the arrow mark.

2. Echolocation of an oscillating object

2.1 Setup

Turn off the air blower, move away the photogate and the reflecting glider.

Bring the transmitter and receiver at a distance of ~ 3 cm and arrange their stand at about 25 cm in front of the polyethylene disk coupled to the jigsaw motor. Make sure the directions of sent/received ultrasound are properly aligned.

Turn the jigsaw on and slowly increase the oscillation frequency until it reaches ~ 1 Hz. Oscilloscope setup: CH1: 2V/cm, HORIZONTAL: 50 ms/cm. Press RUN/STOP to analyze the display. You will notice a pattern resulting from the superposition of the low frequency oscillation and the sinusoidal Doppler waveform. Read the Doppler shift frequency (use the CURSOR, align the left and right cursor lines over two successive maxima).

Use the simplified Doppler equation to calculate the speed of the oscillating disk.

Please note that the detection system does not distinguish between the forward and the reverse directions of travel.

This experiment was designed by Ruxandra M. Serbanescu and built by Robert Smidrovskis in 2004-2005

¹M.A Quinones et al: *Recommendations for quantification of Doppler echocardiography: A report from the Doppler Quantification Task Force of the Nomenclature and Standards Committee of the American Society of Echocardiography.* J. Am Soc. Echocardiogr. 2002; 15:167-184