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# General Physics (2) for Engineering

## SOUND WAVES

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# Sound waves

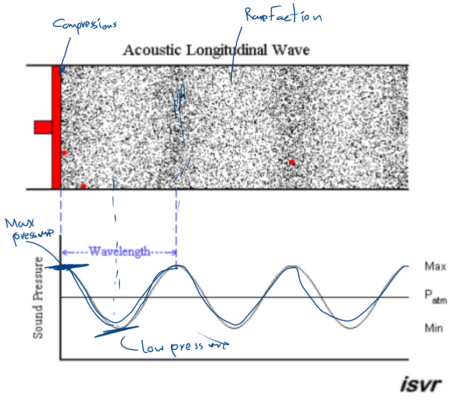
موجات الصوت

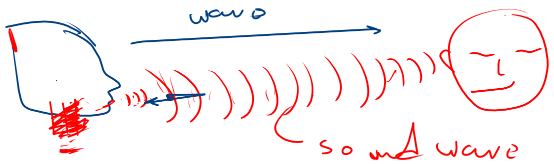
- Sound waves are the most common example of longitudinal waves.
- Sound can travel through gas, liquid, and solids.

**How is sound created?**

بيأثر على الوسط المحيط بالمصدر

Vibration of the source affects the density of the medium instantly and create region of high density and high pressure (compressions) and low density and low pressure (rarefactions), and moves as a longitudina wave.



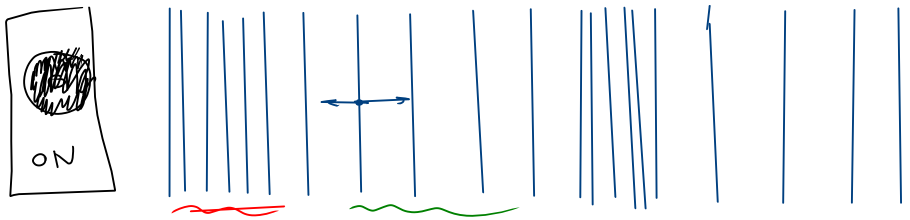




Medium

gas, Liquid, solid

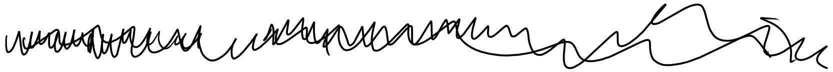
Longitudinal waves

sound wave




Compressions

Rarefaction



Frequency

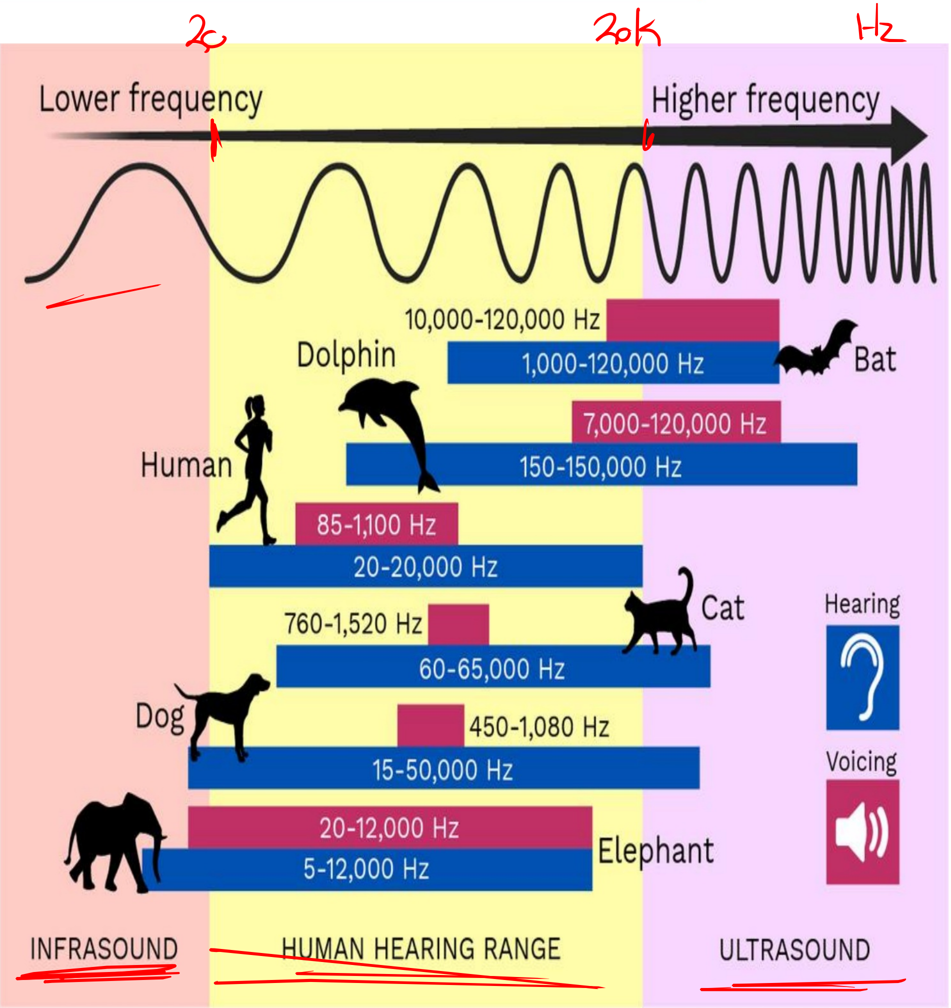
The Sound waves are divided into three categories that cover different frequency ranges:

1- *Audible waves*: These are sound waves with frequencies ranging from 20 Hz to 20,000 Hz (20 kHz)

10, 15, 18

2- *Infrasonic waves:* have frequencies **below** the audible range Examples include sounds produced by earthquakes and volcanic eruptions

3- *Ultrasonic waves:* have frequencies **above** the audible range They are commonly used in medical imaging (sonograms)



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# Speed of Sound Waves

* The speed of sound waves in a medium depends on the compressibility ($1/B$) and density of the medium $\rho$. If the medium is a liquid or a gas and has a bulk modulus $B$ (elastic property of the medium) and density $\rho$ (inertial property of the medium ), the speed of sound waves in that medium is :

$$v = \sqrt{\frac{B}{\rho}} \quad \text{where} \quad B_{\text{bulk modulus}} = \frac{\Delta P}{-\Delta V / V} = -V\frac{dP}{dV}$$

$$\rho = \text{density}$$

Larger B~>medium is harder to compress~>sound travels faster
Larger $\rho$~ > more inertia ~> sound travels slower

* The speed of sound also depends on the temperature of the medium. For sound traveling through air, the relationship between wave speed and medium temperature is :

$$v = (331\text{ m/s})\sqrt{1 + \frac{T_C}{273°C}}$$

where 331 m/s is the speed of sound in air at 0°C, and $T_c$ is the air temperature in degrees.

**Speed of Sound in Various Media**

| Medium | $v$ (m/s) |
|---|---|
| **Gases** | |
| Hydrogen (0°C) | 1 286 |
| Helium (0°C) | 972 |
| Air (20°C) | 343 |
| Air (0°C) | 331 |
| Oxygen (0°C) | 317 |
| **Liquids at 25°C** | |
| Glycerol | 1 904 |
| Seawater | 1 533 |
| Water | 1 493 |
| Mercury | 1 450 |
| Kerosene | 1 324 |
| Methyl alcohol | 1 143 |
| Carbon tetrachloride | 926 |
| **Solids**[a] | |
| Pyrex glass | 5 640 |
| Iron | 5 950 |
| Aluminum | 6 420 |
| Brass | 4 700 |
| Copper | 5 010 |
| Gold | 3 240 |
| Lucite | 2 680 |
| Lead | 1 960 |
| Rubber | 1 600 |

* speed oF Sound waves

it depends on Medium :-

1) Compressibilty $= \frac{1}{B}$ → Bulk modulus $= \frac{-P}{\frac{\Delta V}{V_0}}$

pressure

→ change in volume oF medium

→ initial volume

2) density $= \rho$

3) Teperature

$$\boxed{V = \sqrt{\frac{B}{\rho}}}$$

m/s

- if B is Large → V will be large $\quad V \propto B$
  not easily Compressed
- if $\rho$ is Large → V will be small $\quad V \propto \frac{1}{\rho}$

→ in Air $\quad \boxed{V = (331)\sqrt{1 + \frac{T°_c}{273°}}}$ → Temperature oF Air

speed at 0°c

## Example

**(A)** Find the speed of sound in water, which has a bulk modulus of $2.1 \times 10^9\ \mathrm{N/m^2}$ at a temperature of 0°C and a density of $1.00 \times 10^3\ \mathrm{kg/m^3}$.

***Solution*** Using Equation 17.1, we find that

$$v_{\text{water}} = \sqrt{\frac{B}{\rho}} = \sqrt{\frac{2.1 \times 10^9\ \mathrm{N/m^2}}{1.00 \times 10^3\ \mathrm{kg/m^3}}} = 1.4\ \mathrm{km/s}$$

In general, sound waves travel more slowly in liquids than in solids because liquids are more compressible than solids. Note that the speed of sound in water is lower at 0°C than at 25°C (Table 17.1).

$v_{solid} > v_{liquid} > v_{gas}$

| Substance | Speed of sound (m/s) |
|---|---|
| Steel | 5050 |
| Water | 1493 |
| Helium | 350 (at 0°C) |

Givens :-

$B = 2.1 \times 10^9\ N/m^2$

$\rho = 1 \times 10^3\ Kg/m^3$

$$v = \sqrt{\frac{B}{\rho}} = \sqrt{\frac{2.1 \times 10^9\ N/m^2}{1 \times 10^3\ Kg/m^3}}$$

$$= \boxed{1.44 \times 10^3\ m/s}$$

$$\boxed{1.4\ Km/s}$$

$\frac{E}{t} = P$

$\frac{P}{A}$

## Sound Intensity

We define the ***intensity of a wave I*** as the power per unit area or the rate at which the energy being transported by the wave transfers through a unit area A perpendicular to the direction of travel of the wave:

$$I = \frac{P}{A_{area}}$$

SI unit : $W/m^2$

Since the sound wave distributes in all directions(spherical) then the intensity of a uniform spherical wave is

$$I = \frac{P}{4\pi r^2}$$

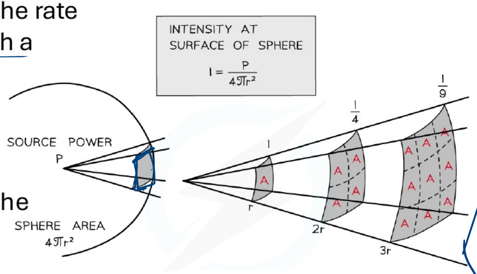
The intensity decreases in proportional to the square of the distance from the source.

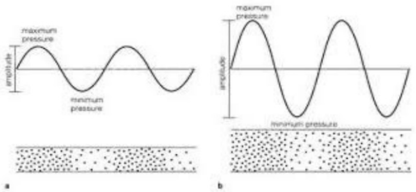
The intensity of a wave is proportional to the square of its amplitude.

$$I \propto \boxed{A^2_{amp}}$$

$P \propto A^2$

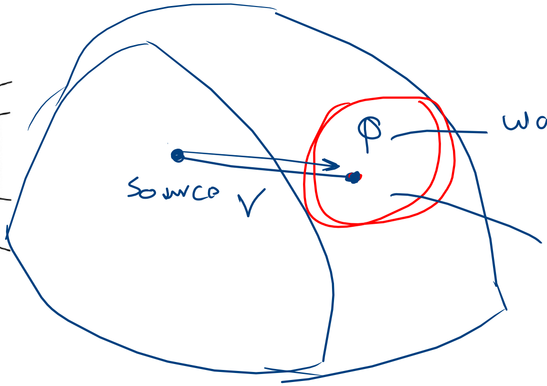
$$\boxed{I \propto \frac{A^2}{r^2}}$$

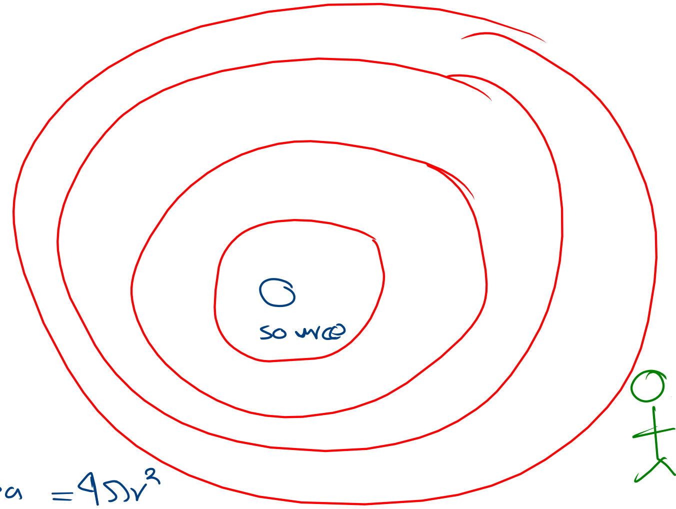


sound intensity شدة الصوت

$I = \frac{P}{A}$ $\frac{watt}{m^2}$




Area $= 4\pi r^2$

$$\boxed{I = \frac{P}{4\pi r^2}}$$

power

distance From source

$I \propto \frac{1}{r^2}$

مربع المسافة من المصدر

## Example

A point source emits sound waves with an average power output of 80.0 W.

**(A)** Find the intensity 3.00 m from the source.

***Solution*** A point source emits energy in the form of spherical waves. Using Equation 17.7, we have

$$I = \frac{\mathcal{P}_{av}}{4\pi r^2} = \frac{80.0\ \text{W}}{4\pi(3.00\ \text{m})^2} = \boxed{0.707\ \text{W/m}^2}$$

an intensity that is close to the threshold of pain.

**(B)** Find the distance at which the intensity of the sound is $1.00 \times 10^{-8}$ W/m$^2$.

***Solution*** Using this value for $I$ in Equation 17.7 and solving for $r$, we obtain

$$r = \sqrt{\frac{\mathcal{P}_{av}}{4\pi I}} = \sqrt{\frac{80.0\ \text{W}}{4\pi(1.00\times 10^{-8}\ \text{W/m}^2)}}$$

$$= \boxed{2.52\times 10^4\ \text{m}}$$

which equals about 16 miles!

Givens:- $P = 80$ watt

a) $I = ?$ , $r = 3$m

$$I = \frac{P}{4\pi r^2} = \frac{80}{4\pi(3)^2} = \boxed{0.707\ \text{w/m}^2}$$

b) $r = ?$ $I = 1\times10^{-8}$ w/m$^2$

$$I = \frac{P}{4\pi r^2} \longrightarrow 4\pi r^2 = \frac{P}{I} \qquad \div 4\pi$$

$$r^2 = \frac{P}{4\pi I}$$

$$r = \sqrt{\frac{P}{4\pi I}} = \sqrt{\frac{80}{4\pi(1\times10^{-8})}}$$

$$= \boxed{2.52\times10^4\ \text{m}}$$

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## Sound Level in Decibels

Sound level β is defined by the equation:

w/m²

$$\beta = 10 \log \left( \frac{I}{I_0} \right)$$

The constant $I_0$ is the reference intensity, taken to be at the threshold of hearing ,

$$I_0 = 1.00 \times 10^{-12}\ \mathrm{W/m^2}$$

and I is the intensity in watts per square meter, where β is measured in decibels (dB).

Note that we use a logarithmic scale due to the range of intensities the human ear can detect is so wide.

Sound Level (dB)

1 W/m2 — 1×10⁹ w/m²

Threshold intensity = $1 \times 10^{-?}$ w/m²

أقل شدة صوت الإنسان يقدر يسمعها

$\beta = 10 \operatorname{Log}_2 \left( \frac{I}{I_0} \right) = dB$

## Example

Two identical machines are positioned the same distance from a worker. The intensity of sound delivered by each machine at the location of the worker is $2.0 \times 10^{-7}\ W/m^2$. Find the sound level heard by the worker

**(A)** when one machine is operating

**(B)** when both machines are operating.

***Solution***

(A) The sound level at the location of the worker with one machine operating is calculated from Equation 17.8:

$$\beta_1 = 10 \log\left(\frac{2.0 \times 10^{-7}\ W/m^2}{1.00 \times 10^{-12}\ W/m^2}\right) = 10 \log(2.0 \times 10^5)$$

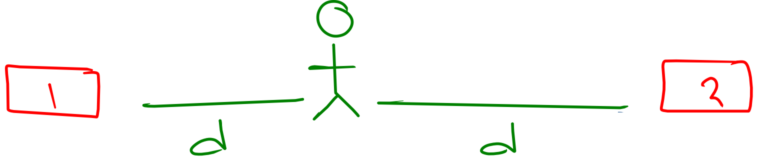
$$= 53\ dB$$

(B) When both machines are operating, the intensity is doubled to $4.0 \times 10^{-7}\ W/m^2$; therefore, the sound level now is

$$\beta_2 = 10 \log\left(\frac{4.0 \times 10^{-7}\ W/m^2}{1.00 \times 10^{-12}\ W/m^2}\right) = 10 \log(4.0 \times 10^5)$$

$$= 56\ dB$$

From these results, we see that when the intensity is doubled, the sound level increases by only 3 dB.




Givens :- $I_1 = I_2 = 2\times10^{-7}\ w/m^2$

a) $I = 2\times10^{-7}\ w/m^2$

$$\beta = 10 \log\left(\frac{I}{I_0}\right)$$

$$= 10 \log\left(\frac{2\times10^{-7}}{1\times10^{-12}}\right) = \boxed{53\ dB}$$

b) Total $I = I_1 + I_2 = 2(2\times10^{-7})\ w/m^2$

$$\beta = 10 \log\left(\frac{4\times10^{-7}}{1\times10^{-12}}\right) = \boxed{56\ dB}$$

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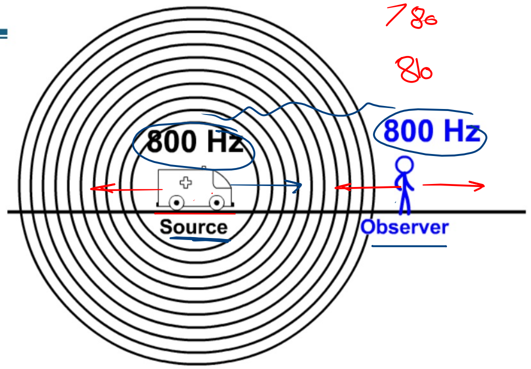
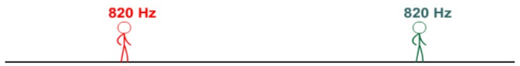
# The Doppler Effect

The Doppler Effect refers to the change in frequency (or wavelength) of a wave concerning an observer who is moving relative to the source of the wave. It's a phenomenon observed with all types of waves, including sound waves

## No Doppler Effect with No Relative Motion




## Doppler Effect of Sound




## Case 1: The ***Observer*** Is Moving Relative to a Stationary Source

speed of wave

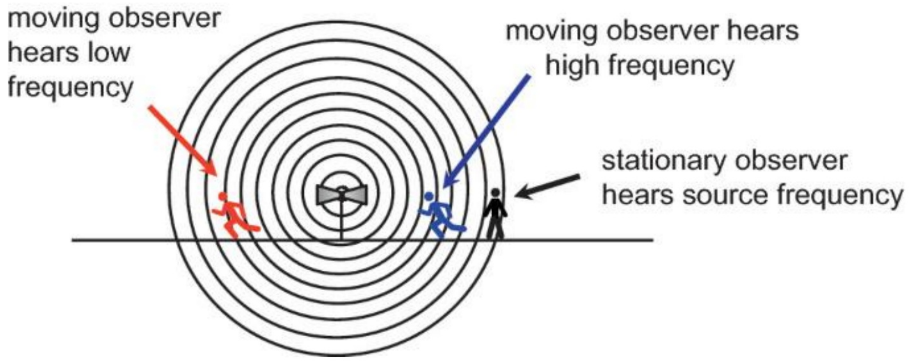
$$f' = \left(\frac{v + v_O}{v}\right) f \quad \text{(observer moving toward source)}$$

New

source

speed of observe

$$f' = \left(\frac{v - v_O}{v}\right) f \quad \text{(observer moving away from source)}$$

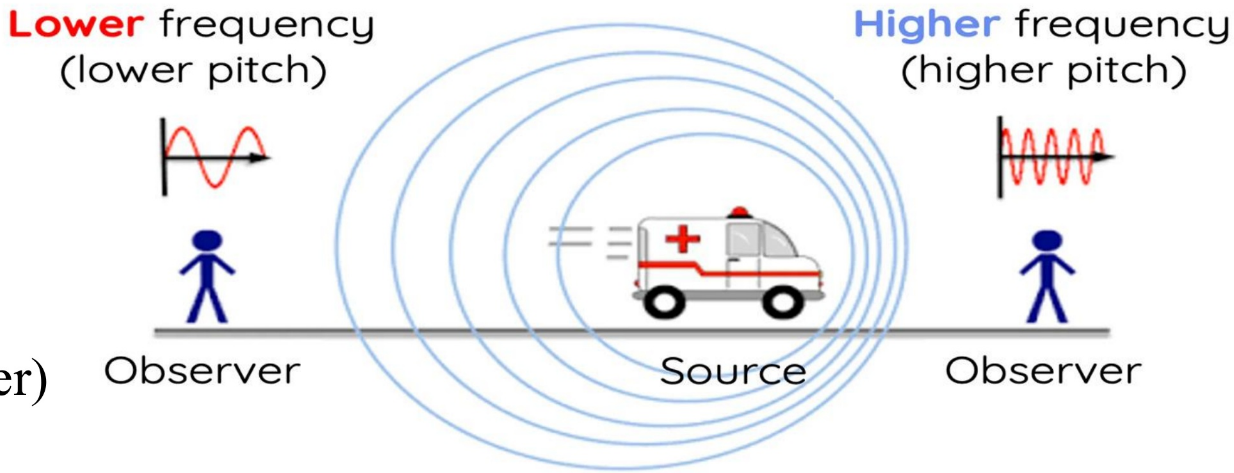



## Case 2: The ***Source*** Is Moving Relative to a Stationary Observer

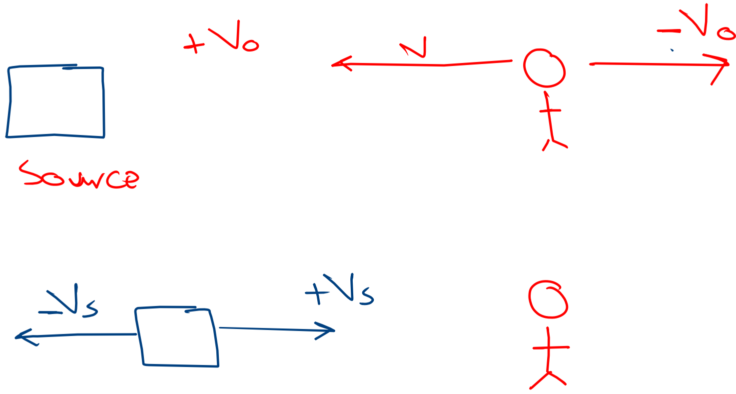
$$f' = \left(\frac{v}{v - v_S}\right) f \quad \text{(source moving toward observer)}$$

speed of source

$$f' = \left(\frac{v}{v + v_S}\right) f \quad \text{(source moving away from observer)}$$



$$F' = \left(\frac{V + (V_o)}{V - (V_s)}\right) F$$




General Case: The formula to calculate the observed frequency $f'$ due to the Doppler Effect for is

doppler Frequency

observer

$$f' = \left(\frac{v + v_O}{v - v_S}\right) f$$

source

Where:

- $f$ = original frequency of the source
- $v$ = velocity of the wave
- $v_o$ = velocity of the observer relative to the medium
- $v_s$ = velocity of the source relative to the medium

$v_o, v_s$ $\begin{cases} \text{A } \textbf{positive} \text{ value is used for motion of the observer or the source } \textbf{toward} \text{ the other} \\ \text{A } \textbf{negative} \text{ value is used for motion of the observer or the source } \textbf{away from} \text{ the other} \end{cases}$

The word **toward** is associated with an increase in observed frequency.
The words **away from** are associated with a decrease in observed frequency.

## Example

A submarine (sub A) travels through water at a speed of 8.00 m/s, emitting a sonar wave at a frequency of 1 400 Hz. The speed of sound in the water is 1 533 m/s. A second submarine (sub B) is located such that both submarines are traveling directly toward one another. The second submarine is moving at 9.00 m/s.

**(A)** What frequency is detected by an observer riding on sub B as the subs approach each other?

**(A)** We use Equation 17.13 to find the Doppler-shifted frequency. As the two submarines approach each other, the observer in sub B hears the frequency

$$f' = \left(\frac{v + v_O}{v - v_S}\right) f$$

$$= \left(\frac{1\,533\,\text{m/s} + (+9.00\,\text{m/s})}{1\,533\,\text{m/s} - (+8.00\,\text{m/s})}\right)(1\,400\,\text{Hz}) = 1\,416\,\text{Hz}$$

$V_s = 8m/s$ $\qquad$ $V_o = 9m(s)$


Source

$F = 1400$ Hz

$V = 1533$ m/s

a) $V_s = +8m/s$ , $V_o = +9m(s)$

$$F' = \left(\frac{V + V_o}{V - V_s}\right) F = \left(\frac{1533 + (9)}{1533 - (+8)}\right)(1400)$$

$$= \boxed{1416\ Hz}$$

b)


$V_o = -9m/s$ $\qquad$ $V_s = -8m/s$

$$F' = \left(\frac{1533 + (-9)}{1533 - (-8)}\right)(1400) = \boxed{1385\ Hz}$$

A submarine (sub A) travels through water at a speed of 8.00 m/s, emitting a sonar wave at a frequency of 1 400 Hz. The speed of sound in the water is 1 533 m/s. A second submarine (sub B) is located such that both submarines are traveling directly toward one another. The second submarine is moving at 9.00 m/s.

**(B)** The subs barely miss each other and pass. What frequency is detected by an observer riding on sub B as the subs recede from each other?

**(B)** As the two submarines recede from each other, the observer in sub B hears the frequency

$$f' = \left(\frac{v + v_O}{v - v_S}\right) f$$

$$= \left(\frac{1\,533\ \mathrm{m/s} + (-9.00\ \mathrm{m/s})}{1\,533\ \mathrm{m/s} - (-8.00\ \mathrm{m/s})}\right)(1\,400\ \mathrm{Hz}) = \boxed{1\,385\ \mathrm{Hz}}$$

# Homework

1- Find the speed of sound in mercury, which has a bulk modulus of approximately $2.80 \times 10^{10}$ N/m$^2$ and a density of 13 600 kg/m$^3$.

2- A train is moving parallel to a highway with a constant speed of 20.0 m/s. A car is traveling in the same direction as the train with a speed of 40.0 m/s. The car horn sounds at a frequency of 510 Hz, and the train whistle sounds at a frequency of 320 Hz. (a) When the car is behind the train, what frequency does an occupant of the car observe for the train whistle? (b) After the car passes and is in front of the train, what frequency does a train passenger observe for the car horn?

3- A vacuum cleaner produces sound with a measured sound level of 70.0 dB. (a) What is the intensity of this sound in W/m$^2$? (b) What is the pressure amplitude of the sound?