Electromechanical Systems
ASE 375

Lecture 23/24: Acoustics Measurements

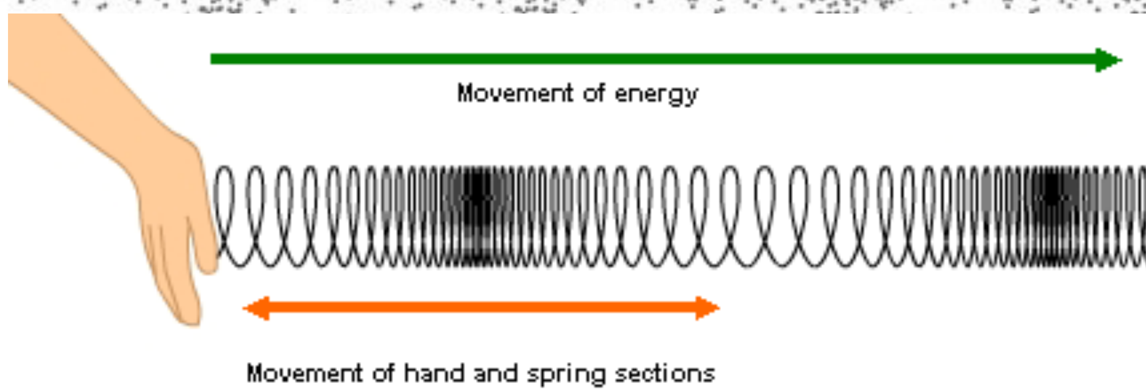
Acoustics Areas of Study

- **Architectural Acoustics** deals with sound in and around buildings of all kinds. Good acoustical design ensures efficient distribution of desirable sounds and exclusion of undesirable sound.
- **Musical Acoustics** deals with the way in which we hear and perceive musical sound, the instruments that produce it, and the structure of melody and harmony. It combines elements of both the arts and science.
- **Noise Control** has been receiving increasing recognition as one of our critical environmental pollution problems. It is a serious threat to the quality of life. Noise-induced hearing loss is a major health problem. Noise also robs us of sleep and interferes with communication. Noise pollution also degrades biodiversity.
- **Underwater Acoustics** The use of acoustic energy to "see" or detect objects underwater is analogous to the use of radar for detecting objects in air. Underwater vessels such as submarine are guided through the depths of the ocean by their acoustic systems.
- **Bioacoustics and Medical Acoustics** deals with the interaction of sound waves with biological tissues in humans and animals, including speech and hearing.
- **Engineering Acoustics** deals with transducers and sound measuring instruments of all kinds. A microphone converts sound energy into electrical energy, a loudspeaker converts electrical energy into sound energy.

What is Sound?

- Sound is a variation of velocity and pressure.
- Sound is transmitted through a gas as a result of collisions between randomly moving molecules.
- Conditions in the gas vary infinitesimally before and after the disturbance passes through.
- <u>Speed of Sound</u>: defined as the speed at which small (reversible) disturbances travel into a quiescent gas.

Think about a slinky



Acoustics Equation

Starting with the Navier-Stokes Equations

Along x

$$\boxed{\rho\frac{\partial u}{\partial t}}+\boxed{\rho u\frac{\partial u}{\partial x}+\rho v\frac{\partial u}{\partial y}+\rho w\frac{\partial u}{\partial z}}=\boxed{-\frac{\partial p}{\partial x}}+\boxed{\frac{\partial}{\partial x}\left(\lambda\nabla\cdot\mathbf{V}+2\mu\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left[\mu\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}\right)\right]+\frac{\partial}{\partial z}\left[\mu\left(\frac{\partial u}{\partial z}+\frac{\partial w}{\partial x}\right)\right]}$$

Unsteady — Convective — Pressure — Viscous

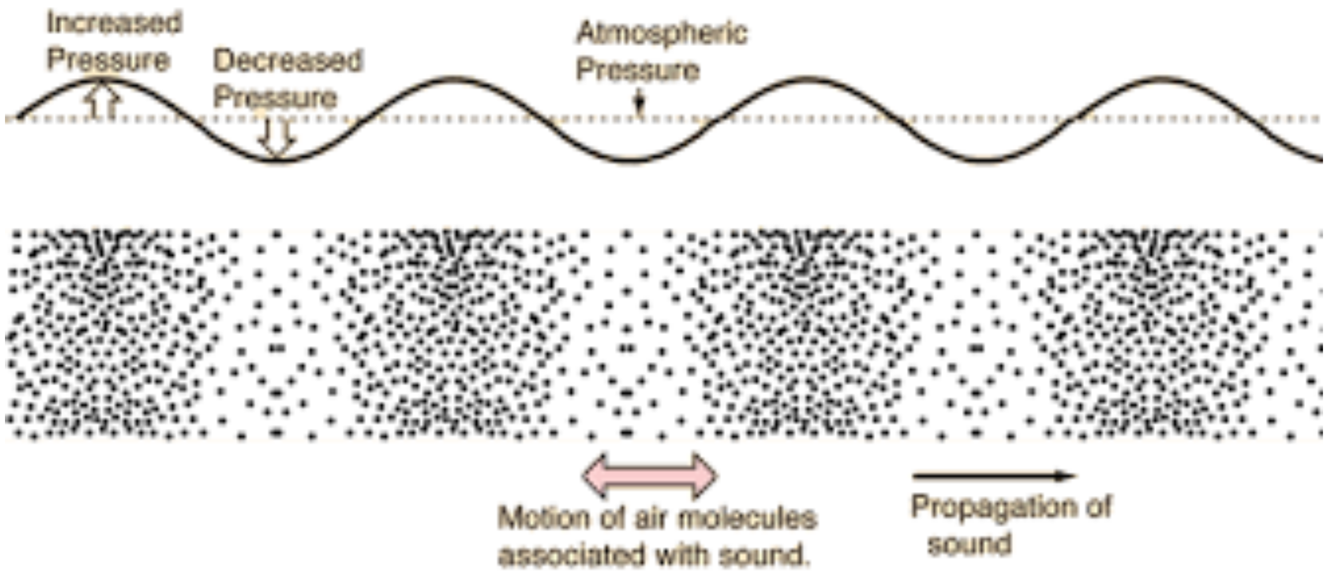
- We make an assumption that acoustic waves represent a small perturbation from the mean

$$p=p_0+p'$$
$$\rho=\rho_0+\rho'$$
$$v_i=0+v_i'$$

- These assumptions help us rewrite the Navier-Stokes equations in the form,
- $\dfrac{\partial^2 p\prime}{\partial x^2}$ - $\left(\dfrac{1}{q^2}\right)\dfrac{\partial^2 p\prime}{\partial t^2}$ = 0
- The solution to this is the wave equation, with a characteristic wave speed

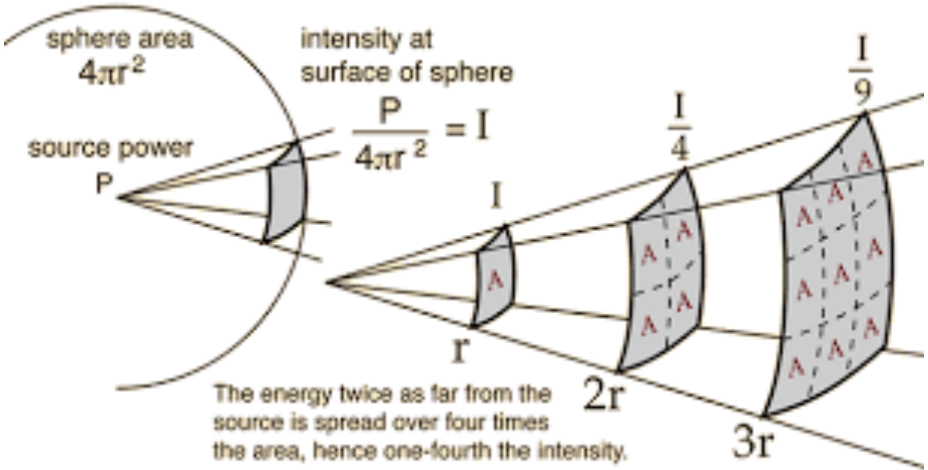
$$a=\left(\frac{du}{d\rho/\rho}\right)_{isentropic}=\sqrt{\frac{dp}{d\rho}}_{isentropic}=\sqrt{\gamma RT}$$

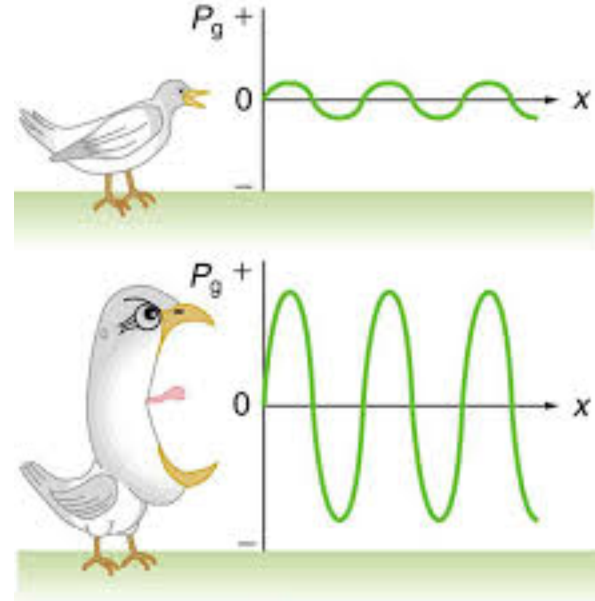
Sound Pressure vs Intensity



- Atmospheric pressure is 101325 N/m^2 (Pa)
- Acoustic pressure variations from this mean are typically a few micro-Pascals to a few Pascals!!
- Intensity of a sound wave is related to its pressure and velocity, by $I = pV$
- The pressure in the wave is related to velocity by $p = \rho a V$
- Therefore, $I = \frac{p^2}{\rho a}$

Power and Intensity of Sound



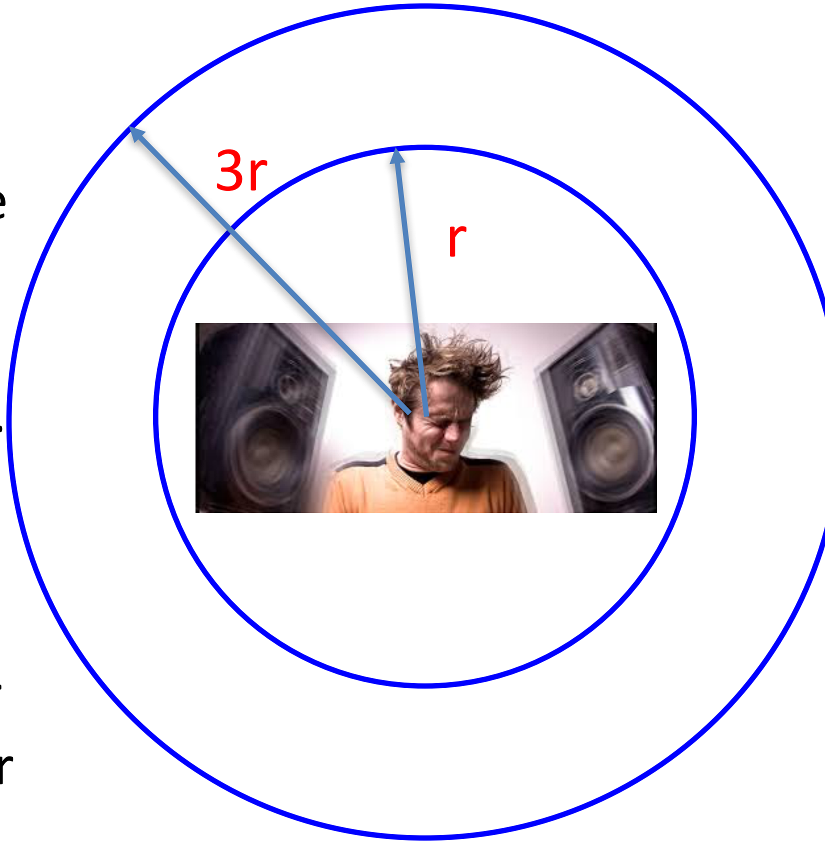


- All waves carry energy.
- Since wave motion involves time variation, it is convenient to talk about sound power (energy per unit time), instead of sound energy.
- The more power a sound wave transmits through a given area in a given amount of time, the more intensity it has, and the louder it will sound.
- That is, intensity is power per unit area: $I = P/A$

Intensity Example

If you sit three times the distance from a set of speakers, how many times lesser will the intensity be?

- Assume the wave fronts are approximately spherical
- The area of a sphere is proportional to the square of its radius ($A = 4 \pi r^2$)
- The intensity is inversely propotional to the square of the distance (since $I = P / A$).
- So, cutting the distance by a factor of 3 will make the intensity about nine times lower.
- However, our ears do not work on a linear scale, so this does not mean 9 times lesser loudness



Threshold Intensity and Range

- Normal sounds carry small amounts of energy, but our ears are very sensitive.
- In fact, we can hear sounds with intensities as low as 10^{-12} W/m^2!
- This is called the threshold intensity, I_0

Source	Intensity
Threshold of Hearing (TOH)	$1*10^{-12}$ W/m^2
Rustling Leaves	$1*10^{-11}$ W/m^2
Whisper	$1*10^{-10}$ W/m^2
Normal Conversation	$1*10^{-6}$ W/m^2
Busy Street Traffic	$1*10^{-5}$ W/m^2
Vacuum Cleaner	$1*10^{-4}$ W/m^2
Large Orchestra	$6.3*10^{-3}$ W/m^2
Walkman at Maximum Level	$1*10^{-2}$ W/m^2
Front Rows of Rock Concert	$1*10^{-1}$ W/m^2
Threshold of Pain	$1*10^{1}$ W/m^2
Military Jet Takeoff	$1*10^{2}$ W/m^2
Instant Perforation of Eardrum	$1*10^{4}$ W/m^2

- If you consider an area of 1 m^2 and sound waves impinging on it every second, the energy threshold level is 10^{-12} J.
- In simple terms, this is the energy required to lift a 1 micro-gram weight through 10 microns.
- The human ear has an incredible range of 16 orders of magnitude, from Threshold to Hearing to Ear Drum Failure – Can you think of any instrument with that range?

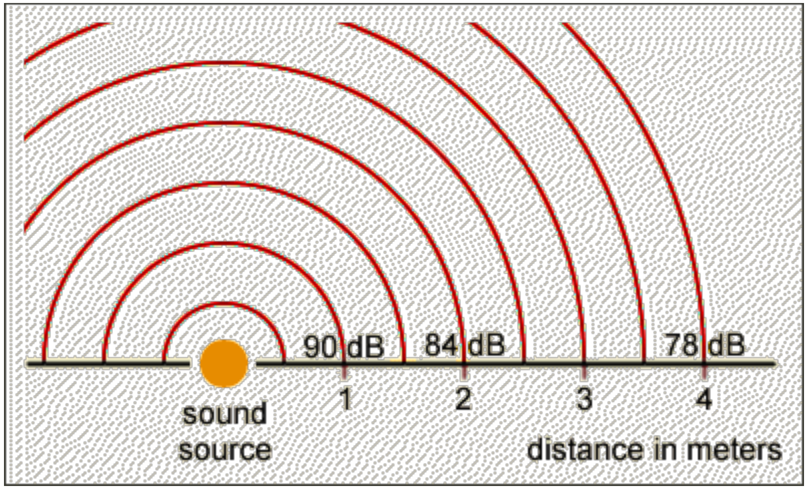
Sound Level (Loudness) in Decibels

- The greater the intensity of a sound at a certain place, the louder it will sound.
- But doubling the intensity will not make it seem twice as loud.
- Experiments show that the intensity must increase by about a factor of 10 before the sound will seem twice as loud to us.
- A sound with a 100 times greater intensity will sound about 4 times louder.
- Therefore, we measure sound level (loudness) based on a logarithmic scale.
- The sound level in decibels (dB) is given by:

$$L = 10 \log \frac{I}{I_0}$$

Sound Level in Decibels

$$L = 10 \log \frac{I}{I_0}$$



Note: According to this definition, a sound at the intensity level, I_o registers zero decibels:

$$L_0 = 10 \log (10^{-12} / 10^{-12}) = 10 \log (1) = 0 \text{ dB}$$

At a certain distance from a siren, the intensity of the sound waves might be 10^{-5} W/m^2. The sound level at this location would be:

$$10 \log (10^{-5} / 10^{-12}) = 10 \log (10^{7}) = 70 \text{ dB}$$

The Decibel Scale

- The chart below lists the approximate sound levels of various sounds at 1m.
- Listening to music with headphones: 105-120 dB if the volume is cranked up to the maximum setting (earbuds, can add 6-9 dB to the volume)

Source	Decibels
Anything on the verge of being audible	0
Whisper	30
Normal Conversation	60
Busy Traffic	70
Niagara Falls	90
Train	100
Construction Noise	110
Rock Concert	120
Machine Gun	130
Jet Takeoff	150
Rocket Takeoff	180

Constant exposure leads to permanent hearing loss.

← *Pain*

← *Damage*

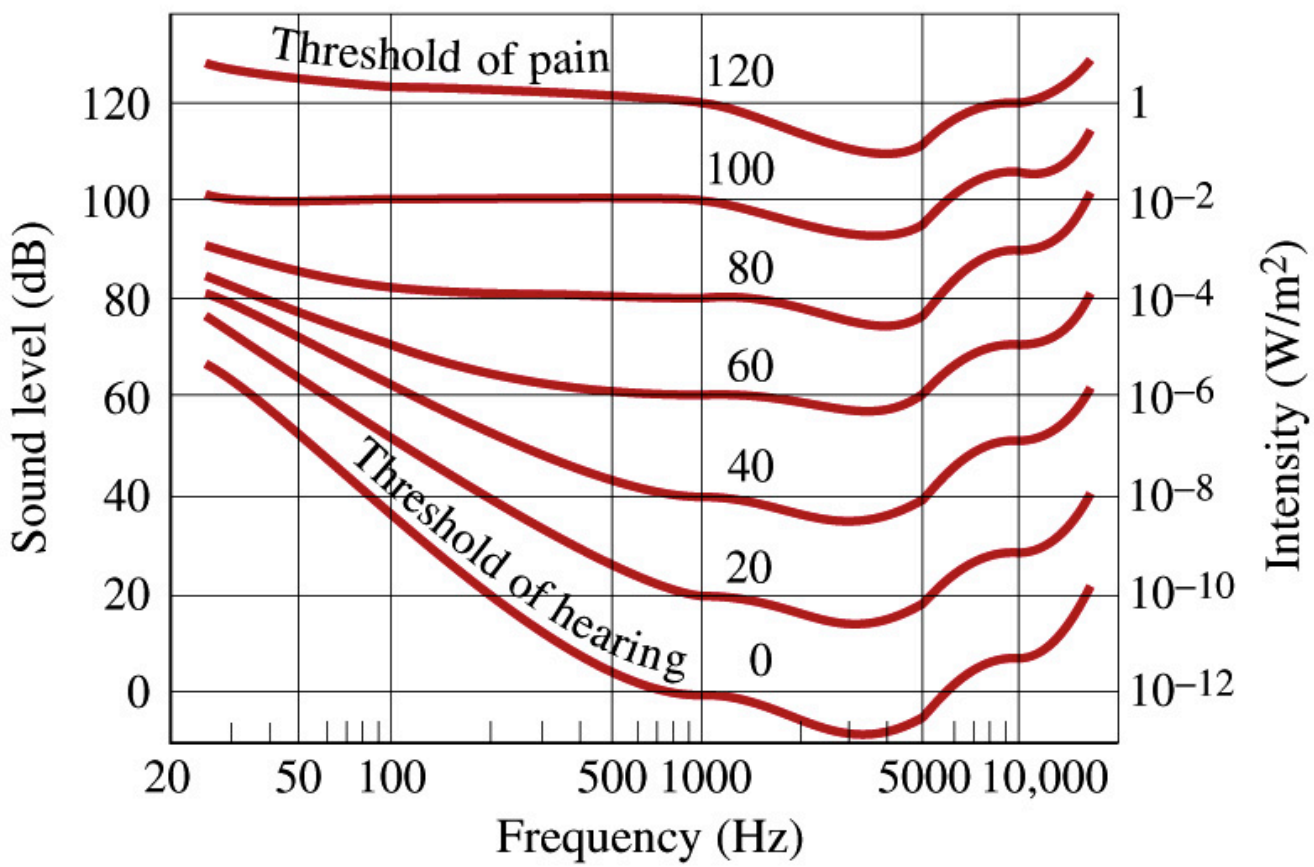
Energy Analysis of Sound

Suppose a 75g egg is dropped from 50 m up onto the sidewalk. The splat takes 0.05 s. Nearly all of the gravitational potential energy the egg had originally is converted into thermal energy, but a very small fraction goes into sound energy. Let's say this fraction is only $7 \cdot 10^{-11}$. How loud is the splat heard from the point at which the egg was dropped?

1. Potential energy of egg initially — 36.8 J
2. Amount of energy converted to sound — $2.6 \cdot 10^{-9}$ J
3. Sound power output of the egg breaking. — $5.2 \cdot 10^{-8}$ W
4. Sound Intensity at 50 m up.
   (Assume /hemispherical wave fronts.) — $3.3 \cdot 10^{-12}$ W/m^2
5. Sound level in decibels. — 5.2 dB, very faint

Sound Level vs Frequency

$$L = 10\log\left(\frac{\langle I\rangle}{I_0}\right) \qquad I_0 = 1x10^{-12}\ \frac{W}{m^2}$$



Sound Pressure Level

Sound Pressure Level Formula

$$SPL\ (dB) = 10\ log_{10}\left(\frac{p^2}{p_o{}^2}\right)$$

- SPL (Sound Pressure Level) in dB
- p - sound pressure in Pa
- p_o is reference pressure level

$$I_0 = \frac{p_0^2}{\rho c}$$

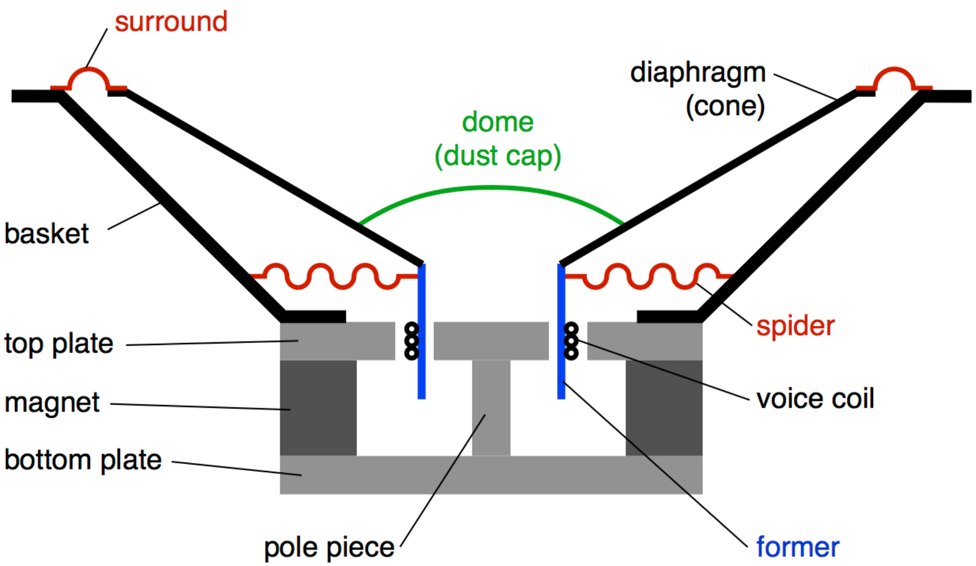
Location	Reference Intensity	Reference Pressure
Air	1×10^{-12} W/m^2	20 μPa

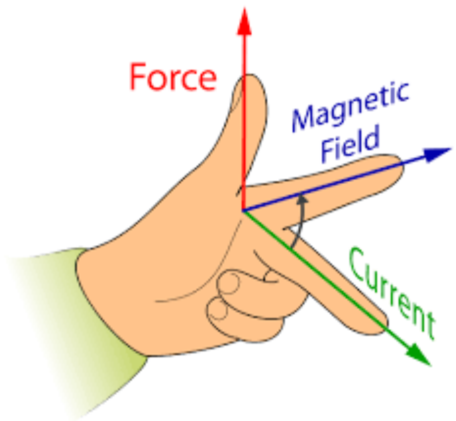
- Why do we need to define SPL?

- Because pressure at a point is easy to measure, while intensity is not
- All acoustic measuring instruments measure local pressure as a function of time

Measuring Sound

Remember how an electromagnetic shaker works
(actually, also a speaker)

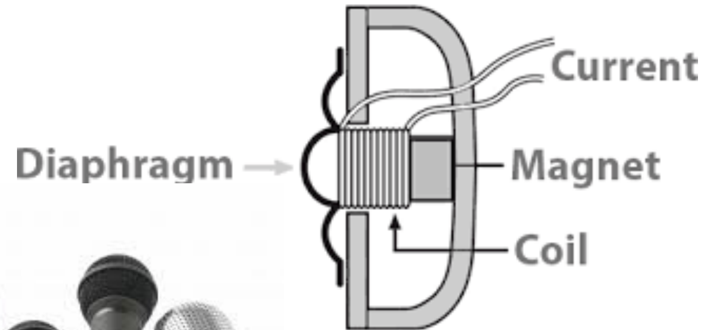


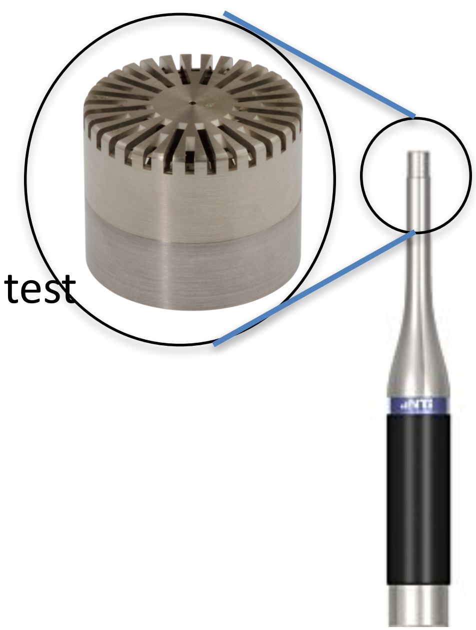


- Force on current carrying coil is up or down depending on direction of current
- An alternating current creates an oscillatory motion
- An electromagnetic shaker (or a speaker) are actuators, i.e, they convert electrical energy into mechanical energy
- Sound is measured using "microphones" which convert sound energy into mechanical movement of a diaphragm, which is then converted into electricity

Primary Types of Microphones

Electromagnet based – Also called Dynamic Microphones, mostly used in music/voice





Capacitance based – Also called Condenser Microphones, used for test and measurement as well as music/voice and small devices

Iphone microphone with embedded electronics