MEASUREMENT
OF
SOUND & NOISE
Introduction

Sound is a form of energy transmitted from a vibrating source. The vibrating matter creates small, repetitive pressure disturbances that are imparted to the air along a path and reach a receiver, the ear. Sound and vibration are created by a source, are transmitted along one or more paths, and reach a receiver.

Measurement unit:

dB SCALE: Acoustic parameters are expressed as logarithmic ratio of the measured value to a reference value. The Bell (B) is a unit of measurement invented by Bell Labs and named after Alexander Graham Bell. The Bell was too large, so the deciBel (dB), equal to 0.1 is B.

Sound characteristics:

Sound is a propagating disturbance in a fluid (gas or liquid) or in a solid. Ear drums sense these small changes in the barometric pressure of the air, distinguishing sounds based on amplitude and pitch. Amplitude refers to the level of energy that reaches the ear which corresponds to how loud we perceive sound. Pitch is the relative quality or the frequency of the sound that reaches the ear, helping a person to identify the source of the sound.

In systems, the source of sound is a combination of different processes, such as turbulence from the fan(s) and mechanical sounds from the motor(s), etc. Frequency, measured in Hertz (Hz), is the number of oscillations (cycles) completed per second by a vibrating object. The sound that humans hear covers a frequency range of about 20 Hz to about 20,000 Hz. Sounds at different frequencies behaves differently, causing humans ears to react to them differently as well.

<20Hz 20Hz to 20000Hz > 20000Hz
Infrasonic Audio Range Ultrasonic

The speed of a longitudinal wave in a fluid is a function of the fluid’s density and bulk modulus of elasticity. In air, at room temperature, the speed of sound is about 340 m/s; in water, about 1500 m/s. In solids, there are several different types of waves, each with a different speed.

Wavelength

The wavelength of sound in a medium is the distance between successive maxima or minima of a simple harmonic disturbance propagating in that medium at a single instant in time. Wavelength, speed, and frequency are related by:

$$\lambda = \frac{c}{f}$$

where: $\lambda$ = wavelength, m, $c$ = speed of sound, m/s, $f$ = frequency, Hz
The speed of sound transmission depends on the physical property of the medium.

For air, the speed varies slightly with temperature change. The speed of sound = a constant (344 m/s) in consideration of narrow temperature range in HVAC systems.

Sound traveling through the air at a frequency of 200 Hz has a wavelength of 1.7 m.

\[
\text{wavelength} = \frac{344 \text{ m/s}}{200 \text{ Hz}} = 1.7 \text{ m}
\]

**Sound Pressure**: evaluation of harmfulness and annoyance of noise sources

**Sound Intensity**: location & rating of noise sources rate of energy flow per unit area

**Sound Power**: for noise rating of machines unique descriptor of noisiness of source

Types of sound sources:
1. **Point source**:
2. **Line source**:
3. **Plane source**:

\[
r: L_p \\
2r: L_p - 6 \text{ dB} \\
r: L_p - 3 \text{ dB}
\]
SOUND BITS:

Unless there is a 3 dB difference in SPL, human beings cannot distinguish the difference in the sound, Sound is perceived as doubled in its loudness when there is 10dB difference in the SPL.

(Remember 6dB change represents doubling of sound pressure)

Ear is not equally sensitive at all frequencies:

- highly sensitive at frequencies between 2kHz to 5kHz
- less at other freq.

This sensitivity dependence on frequency is also dependent on SPL.

**levels**

Magnitude of sound and vibration is almost always expressed in **levels**. As shown in the following equations, the level $L$ is based on the common (base 10) logarithm of a ratio of the magnitude of a physical property (e.g., sound pressure) to a reference magnitude of the same type of property:

$$L = 10 \log \left( \frac{A}{A_{ref}} \right)$$

Where $A$ is the magnitude of the physical property of interest and $A_{ref}$ is the reference. Note that the ratio is dimensionless. In this equation, a factor of 10 is included to convert bels to decibels (dB). This basic equation describes levels of power, intensity, and energy, which are related to the square of other physical properties, such as sound pressure and vibration acceleration. Therefore, levels of magnitude of these quantities can be written as:

$$L = 10 \log \left( \frac{P^2}{P_{ref}^2} \right) = 20 \log \left( \frac{P}{P_{ref}} \right)$$

Where $P$ is the physical quantity, such as the magnitude of acoustic pressure. Numerically, the decibel is ten times the base 10 logarithm of the ratio of two like quantities proportional to acoustical power or energy.

**Sound Pressure and Sound Pressure Level**

Sound waves in air are variations in pressure above and below atmospheric pressure. The human ear responds to a large range of sound pressures. Sound pressure is typically measured in Pascals (Pa), which creates a range of pressure values so wide that it is more convenient to use a logarithmic scale. Therefore, the decibel (dB) scale is preferred because it collapses a large range of pressure values to a more manageable, easier to analyze range. The sound pressure level is measured in dB above a standard reference level and given by:

$$L_p = 10 \log \left( \frac{P^2}{P_{ref}^2} \right) = 20 \log \left( \frac{P}{P_{ref}} \right)$$

Here “$P$” represents the sound pressure being measured and “$P_{ref}$” is the reference sound pressure, typically 20 μPa, which is generally considered the threshold of human hearing.
Sound pressure level is relatively easy to measure and thus is used by most noise codes and criteria. (The human ear and microphones are pressure-sensitive.)

**Why log ratio?**

- Logarithmic scale compresses the high amplitudes and expands the low ones.
- The other reason: Equal relative modifications of the strength of a physical stimulus lead to equal absolute changes in the salience of the sensory events (Weber-Fechner Law) and can be approximated by a logarithmic characteristics.

<table>
<thead>
<tr>
<th>source</th>
<th>SP Pa</th>
<th>SPL dB re20 μPa</th>
<th>Subjective reaction</th>
<th>source</th>
<th>SP Pa</th>
<th>SPL dB re20 μPa</th>
<th>Subjective reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Military jet takeoff at 30 m</td>
<td>200</td>
<td>140</td>
<td>Extreme danger</td>
<td>Conversational speech at 1 m</td>
<td>0.02</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Artillery fire at 3 m</td>
<td>63.2</td>
<td>130</td>
<td></td>
<td>Window air conditioner at 3 m</td>
<td>0.006</td>
<td>50</td>
<td>Moderate</td>
</tr>
<tr>
<td>Passenger jet takeoff at 15 m</td>
<td>20</td>
<td>120</td>
<td>Threshold of pain</td>
<td>Quiet residential area</td>
<td>0.002</td>
<td>40</td>
<td>Quiet</td>
</tr>
<tr>
<td>Loud rock band</td>
<td>6.3</td>
<td>110</td>
<td>Threshold of discomfort</td>
<td>Whispered conversation at 2 m</td>
<td>0.0006</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Automobile horn at 3 m</td>
<td>2</td>
<td>100</td>
<td></td>
<td>Buzzing insect at 1 m</td>
<td>0.0002</td>
<td>20</td>
<td>Perceptible</td>
</tr>
<tr>
<td>large diesel engine</td>
<td>0.6</td>
<td>90</td>
<td>Very loud</td>
<td>Threshold of good hearing</td>
<td>0.00006</td>
<td>10</td>
<td>Faint</td>
</tr>
<tr>
<td>Accelerating diesel truck at 15 m</td>
<td>0.2</td>
<td>80</td>
<td></td>
<td>Threshold of excellent youthful hearing</td>
<td>0.00002</td>
<td>0</td>
<td>Threshold of hearing</td>
</tr>
<tr>
<td>Freight train at 30 m</td>
<td>0.06</td>
<td>70</td>
<td>loud</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Sound Power and Sound Power Level:

Sound ratings are typically provided in terms of the sound power of a source, which is its rate of emission of acoustical energy and is expressed in watts. Sound power does not depend on the distance of observation location from the source but it does depend on operating conditions. The sound power level, \( L_w \), is defined by:

\[
L_w = 10 \log \left( \frac{W}{10^{-12}} \right)
\]

Here “W” is the sound power emitted by the source in watts and \( 10^{-12} \) is the reference power.

Mechanical equipment is rated in terms of sound power level in order to provide a common reference measurement that is independent of distance and the acoustical conditions of the environment. When attempting to measure sound power level ratings, an engineer will find that he cannot measure these ratings directly. Instead, sound power level ratings are calculated from several sound pressure measurements created by a source in a particular test environment using one of four common methods: free-field, reverberation room, progressive wave (in-duct), and sound intensity.

Typical average decibel levels (dBA) of some common sounds:

<table>
<thead>
<tr>
<th>activation</th>
<th>SPL dB</th>
<th>SP W</th>
<th>activation</th>
<th>SPL dB</th>
<th>SP W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold of hearing</td>
<td>0</td>
<td>( 10^{-12} )</td>
<td>Food blender (3 feet), shouting</td>
<td>90</td>
<td>( 10^{-3} )</td>
</tr>
<tr>
<td>Human breath</td>
<td>10</td>
<td>( 10^{-11} )</td>
<td>Subway (inside)</td>
<td>94</td>
<td></td>
</tr>
<tr>
<td>Rustling leaves</td>
<td>20</td>
<td>( 10^{-10} )</td>
<td>Diesel truck (30 feet), heavy truck at high way speed</td>
<td>100</td>
<td>( 10^{-2} )</td>
</tr>
<tr>
<td>Quiet whisper (3 feet)</td>
<td>30</td>
<td>( 10^{-9} )</td>
<td>Power mower (3 feet)</td>
<td>107</td>
<td></td>
</tr>
<tr>
<td>Quiet home</td>
<td>40</td>
<td>( 10^{-8} )</td>
<td>Large HVAC fan</td>
<td>110</td>
<td>( 10^{-1} )</td>
</tr>
<tr>
<td>Quiet street, office air diffuser</td>
<td>50</td>
<td>( 10^{-7} )</td>
<td>Pneumatic riveter (3 feet)</td>
<td>115</td>
<td></td>
</tr>
<tr>
<td>Normal conversation, electronic equipment ventilation fan</td>
<td>60</td>
<td>( 10^{-6} )</td>
<td>Chainsaw (3 feet)</td>
<td>117</td>
<td></td>
</tr>
<tr>
<td>Inside car, voice, conversation level</td>
<td>70</td>
<td>( 10^{-5} )</td>
<td>Amplified Rock and Roll (6 feet), small aircraft engine</td>
<td>120</td>
<td>1</td>
</tr>
<tr>
<td>Loud singing (3 feet)</td>
<td>75</td>
<td></td>
<td>Jet plane (100 feet), large pipe organ</td>
<td>130</td>
<td>10</td>
</tr>
<tr>
<td>Automobile (25 feet)</td>
<td>80</td>
<td>( 10^{-4} )</td>
<td>Jet aircraft at takeoff</td>
<td>160</td>
<td>( 10^{4} )</td>
</tr>
<tr>
<td>Motorcycle (30 feet)</td>
<td>88</td>
<td></td>
<td>Space shuttle launch</td>
<td>200</td>
<td>( 10^{8} )</td>
</tr>
</tbody>
</table>
Sound Intensity and Sound Intensity Level:
The sound intensity $I$ at a point in a specified direction is the rate of flow of sound energy (i.e., power) through unit area at that point. The unit area is perpendicular to the specified direction, and the units of intensity are watts per square meter. Sound intensity level $L_I$ is expressed in dB with a reference quantity of $10^{-12}$ W/m², thus:

$$L_I = 10\log\left(\frac{I}{10^{-12}}\right)$$

The instantaneous intensity $I$ is the product of the pressure and velocity of air motion (e.g., particle velocity), as shown here:

$$I = pv$$

Both pressure and particle velocity is oscillating, with a magnitude and time variation. Usually, the time-averaged intensity $I_{ave}$ (i.e., the net power flow through a surface area, often simply called “the intensity”) is of interest.

Combining Sound Levels:
To estimate the levels from multiple sources from the levels from each source, the intensities (not the levels) must be added. Thus, the levels must first be converted to find intensities, the intensities summed, and then converted to a level again. Because sound pressure levels are usually good approximations for sound intensity levels, the combination of two levels $L_1$ and $L_2$ produces a level $L_{\text{sum}}$ given by:

$$L_{\text{sum}} = 10\log\left(10^{L_1/10} + 10^{L_2/10}\right)$$

Where $10^{L_i/10}$ is $p_i^2/p_{\text{ref}}^2$.

This process may be extended to combine as many levels as needed using the following equation:

$$L_{\text{sum}} = 10\log\left(\sum_i 10^{L_i/10}\right)$$

To remove background noise, the levels are unlogged and the square of the background sound pressure subtracted from the square of the sound pressure for the combination of the source and background noise:

$$L_p(\text{source}) = 10\log\left(10^{L_{(\text{comb})}/10} - 10^{L_{(\text{bkgd})}/10}\right)$$

Where $L_{(\text{bkgd})}$ is the sound pressure level of the background noise, measured with the source of interest turned off. If the difference between the levels with the source on and off is greater than 10 dB, then background noise levels are low enough that the effect of background noise on the levels measured with the source on can be ignored.
Octave Bands

Human ear perception: sounds at frequencies 20 to 16,000 Hz.

HVAC system sounds 45 to 11,200 Hz (11,156 data points).

HVAC sounds frequencies \( \rightarrow \) smaller ranges (octave bands).

The highest frequency in the band is two times the lowest frequency.

Center frequency = square root of the product of the lowest and highest frequencies in the band.

The frequency range (45 to 11,200 Hz) \( \rightarrow \) eight octave bands with center frequencies of 63, 125, 250, 500, 1,000, 2,000, 4,000, and 8,000 Hz.

<table>
<thead>
<tr>
<th>octave band</th>
<th>center frequency (Hz)</th>
<th>frequency range (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>63</td>
<td>45 to 90</td>
</tr>
<tr>
<td>2</td>
<td>125</td>
<td>90 to 180</td>
</tr>
<tr>
<td>3</td>
<td>250</td>
<td>180 to 355</td>
</tr>
<tr>
<td>4</td>
<td>500</td>
<td>355 to 710</td>
</tr>
<tr>
<td>5</td>
<td>1,000</td>
<td>710 to 1,400</td>
</tr>
<tr>
<td>6</td>
<td>2,000</td>
<td>1,400 to 2,800</td>
</tr>
<tr>
<td>7</td>
<td>4,000</td>
<td>2,800 to 5,600</td>
</tr>
<tr>
<td>8</td>
<td>8,000</td>
<td>5,600 to 11,200</td>
</tr>
</tbody>
</table>

Analyzing Sound Ratings

The purpose of developing sound ratings is to help determine whether or not the equipment will cause a sound problem. Sound becomes noise when it is too loud, unexpected, contains unwanted tones (e.g., a whine, whistle, or hum), or is unpleasant. Sound only has to be unwanted for it to be noise, not necessarily just loud. Humans respond differently to each particular frequency of sound, making the ear more receptive to certain frequencies than others.

As mentioned before, sound is a combination of frequencies. This creates a problem for measuring the impact of each sound on human hearing since each frequency will be perceived differently by the ear.

MEASURING SOUND

Instrumentation: The basic instrument for measuring sound is a sound level meter, which comprises a microphone, electronic circuitry, and a display device. The microphone converts sound pressure at a point to an electronic signal, which is then processed and the sound pressure level displayed using analog or digital circuitry. Sound level meters are usually battery-operated, light, handheld units with outputs that vary in complexity depending on cost and level of technology.

Sophisticated sound measurements and their procedures should be carried out by individuals experienced in acoustic measurements. At present, there are only a few noise standards that can be used to measure interior sound levels from mechanical equipment (e.g., ASTM Standards E1573 and E1574).

The infections on sound measurement:

1. Sound reflecting from neighboring surface.
2. Sound transitioning by base or background noise.
3. Other sound sources and Magnitude of sound sources and Directivity of source.
4. Room volume
5. Room furnishings and surface treatments
6. Distance from sound sources to point of observation.
Measuring location:

Outdoor measuring: When measuring the noise, the background noise from other sources (occupants, wind, nearby traffic, elevators, etc.) must be determined. Sometimes the sound from a particular piece of equipment must be measured in the presence of background sound from sources that cannot be turned off, such as automobile traffic or certain office equipment. Important issues such as the effect of large, nearby sound-reflecting surfaces and weather conditions such as wind, temperature, and precipitation must be addressed.

Indoor measuring: a specified room noise criterion must demonstratively be met. Measurement procedures for obtaining the data to demonstrate compliance are often not specified which can lead to confusion when different parties make measurements using different procedures, because the results often do not agree. The problem is that most rooms exhibit significant point-to-point variation in sound pressure level. When a noise has no audible tonal components, the differences in measured sound pressure level at several locations in a room may be as high as 3 to 5 dB. However, when audible tonal components are present, especially at low frequencies, the variations due to standing waves that occur at frequencies of resonance may exceed 10 dB. These are generally noticeable to the average listener when moving through the room. Although commissioning procedures usually set precise limits for demonstrating compliance, the outcome can unfortunately be controversial unless the measurement procedure has been specified in detail. At the time of writing, there was no general agreement in the industry on an acoustical measurement procedure for commissioning systems.
Controlling sound:

1- Enclosures and barriers  
2- Partitions  
3- Attenuation and plenums

HUMAN RESPONSE TO SOUND

Noise may be defined as any unwanted sound. Sound becomes noise when it:

- Is too loud—the sound is uncomfortable or makes speech difficult to understand
- Is unexpected (e.g., the sound of breaking glass)
- Is uncontrolled (e.g., a neighbor’s lawn mower)
- Happens at the wrong time (e.g., a door slamming in the middle of the night)
- Contains unwanted pure tones (e.g., a whine, whistle, or hum)
- Contains unwanted information or is distracting (e.g., an adjacent telephone conversation or undesirable music)
- Is unpleasant (e.g., a dripping faucet)
- Connotes unpleasant experiences (e.g., a mosquito buzz or a siren wail)
- Is any combination of the previous examples

To be noise, sound does not have to be loud, just unwanted. In addition to being annoying, loud noise can cause hearing loss, and, depending on other factors, can affect stress level, sleep patterns, and heart rate.

To increase privacy, broadband sound may be radiated into a room by an electronic sound-masking system that has a random noise generator, amplifier, and multiple loudspeakers. Noise from such a system can mask low-level intrusive sounds from adjacent spaces. This controlled sound may be referred to as noise, but not in the context of unwanted sound; rather, it is a broadband, neutral sound that is frequently unobtrusive. It is difficult to design air conditioning systems to produce noise that effectively masks low level intrusive sound from adjacent spaces without also being a source of annoyance.

Types of noise:

Random noise: is an oscillation, the instantaneous magnitude of which cannot be specified for any given instant. The instantaneous magnitudes of a random noise are specified only by probability distributions, giving the fraction of the total time that the magnitude, or some sequence of magnitudes, lies within a specified range (ANSI Standard S1.1). There are three types of random noise: white, pink, and red.

White noise: has a continuous frequency spectrum with equal energy per hertz over a specified frequency range. Because octave bands double in width for each successive band, for white noise the energy
also doubles in each successive octave band. Thus white noise displayed on a 1/3 octave or octave band chart increases in level by 3 dB per octave.

**Pink noise:** has a continuous frequency spectrum with equal energy per constant-pressure bandwidth, such as per octave or 1/3 octave band. Thus pink noise appears on a 1/3 octave or octave band chart as a horizontal line.

**Red noise:** has a continuous frequency spectrum with octave band levels that decrease at a rate of 4 to 5 dB per octave with increasing frequency. Red noise is typical of noise from well-designed HVAC systems.

**Measuring devices:**

![Sound Meter Pro](image)

- 110dB : Rock music, Screaming child
- 100dB : Subway train, Blow dryer
- 90dB : Factory machinery at 3 ft.
- 80dB : Busy street, Alarm clock
- 70dB : Busy traffic, Phone ringtone
- 60dB : Normal conversation at 3 ft.
- 50dB : Quiet office, Quiet street
- **40dB : Quiet residential area, Park**
- 30dB : Quiet whisper at 3 ft, Library
- 20dB : Rustling leaves, Ticking watch
Microphone:

Basic Microphone Types:

1. Dynamic (moving coil)
   - Sound pressure on the diaphragm causes the voice coil to move in a magnetic field
   - The induced voltage mimics the sound pressure
   - Comments
     - Diaphragm and coil must be light
     - Low output impedance – good with long cables
     - Rugged
2. Condenser (capacitor)

- Diaphragm and back plate form a capacitor
- Incident sound waves move the diaphragm, change the separation distance, change the capacitance, create current

**Comments**
- Requires a DC polarizing voltage
- High sensitivity
- Flat frequency response
- Fragile
- High output impedance, nearby pre-amp is necessary
3. Electric:
   - Same basic operation principle as the condenser mic
   - Polarizing voltage is built into the diaphragm
   - Comments:
     - High sensitivity
     - Flat frequency response
     - Fragile
     - High output impedance, nearby pre-amp is necessary

4. Ribbon
   - Conductive ribbon diaphragm moving in a magnetic field generates an electric signal
   - Comments
     - Lightweight ribbon responds to particle velocity rather than pressure
     - Both sides are exposed resulting in a bidirectional response
     - Sensitive to moving air
     - Easily damaged by high sound-pressure levels
5. Piezo-electric (crystal or ceramic):
   - Diaphragm mechanically coupled to a piezoelectric material
   - Piezo (lead zirconate titanate (PZT), barium titanate, rochelle salt) generates electricity when strained
   - Comments:
     - No polarization voltage
     - Generally rugged

6. Shotgun Microphone:
7. Parabolic Microphone

![Parabolic Microphone Diagram]

8. Contact Microphones

![Contact Microphone Images]
9. Pressure Zone Microphone (PZM)
Directivity Patterns:

Single-diaphragm microphones are typically constructed to have one of a variety of directivity patterns:

- Omni directional
- Bidirectional
- Cardioid
- Hyper cardioid
- Super cardioid
- All five

Directivity in 2 dimensions:
Directivity in 3 dimensions:

- Omnidirectional
- Bidirectional
- Cardioid
- Hypercardioid
- Super cardioid
MEASUREMENT OF VIBRATION
Introduction:

What Is Vibration?

Vibration is the physical movement or oscillation of a mechanical part about a reference position.

Vibration is:
- Wasted energy
- A major cause of premature component failure
- Cause of aircraft noise which contributes to crew and passenger discomfort

Terminology:

Prior to any discussion of vibration, it is important to first understand the common terms used for vibration analysis and their applications.

1. **Amplitude**: Amplitude is an indicator of the severity of a vibration. Amplitude can be expressed as one of the following engineering units:
   
i. **Displacement**: Displacement is a measure of the actual distance an object is moving from a reference point.

   ii. **Velocity**: Velocity is the rate of change in position.
      - Typical velocity units are: IPS (Inches Per Second), m/sec (meters per second)
      - Velocity is the most accurate measure of vibration because it is not frequency related.

   iii. **Acceleration**: Acceleration is the rate of change of velocity and is the measurement of the force being produced.
      - Acceleration is expressed in gravitational forces or “G’s”, (1G = 32.17 ft/sec/sec or 9.817 m/s²)
      - Acceleration is frequency related.

2. **Frequencies**: The rate of mechanical oscillation in a period of time. Frequency can be expressed in one of the following units:
   - RPM - Revolutions per Minute
   - CPM - Cycles per Minute
   - CPS - Cycles per Second
   - Hz - Hertz, 1 Hz - 1 Cycle per Second
Types of Vibration:

Vibration can be classified into one or more of the following categories:

1. Periodic:
   - Repeats itself once every time period
   - Result of a mass imbalance in a component or disc.
   - As the component rotates, it produces a “bump” every rotation which is referred to as the once-per-revolution or “1P” vibration.
   - This vibration is usually correctable by balancing.

2. Random:
   - Do not repeat themselves
   - Not related to a fundamental frequency.
   - An example - the shock that is felt as a result of driving down the road and hitting a pothole.

3. Resonant:
   - The natural frequency at which an airframe or mechanical system is inclined to vibrate. All things have one or more resonant frequencies.
   - Resonant vibrations are the result of a response in a mechanical system to a periodic driving force.

4. Harmonic:
   - Exact multiples of a fundamental frequency
   - Classified in terms as 1st, 2nd, 3rd.....

Bandwidth:

- Upper and lower frequency limits of the survey being acquired - either hardware set (with the use of an external band pass filter) or software controlled by the analyzer.
- Setting the frequency bandwidth is a way of eliminating vibration data or noise that is of no interest for your particular application.
- In the survey above, the frequency bandwidth is 0 CPM to 3000 CPM
Resolution:
- The resolution of a spectrum is the number of lines or points used to plot the spectrum.
- The higher the number of lines, the more data acquired.

Equipment:

Sensor: A transducer that converts mechanical motion into electronic signals.

Sensor Selection: The first consideration is manufacturer’s recommendations. If none exist, then:
- Frequency Range
- Environmental conditions

Sensor Installation: Varies depending upon the application. Most manufactures provide the specific location for mounting and this should be strictly adhered to. If these recommendations are not followed, the resulting measurements may be invalid. Generally, mount in a location that provides the closest proximity to the component of interest.

How Vibration Is Analyzed:
- Time Domain - Vibration vs. Time. A vibration signal is presented as a sin wave form with all frequencies and amplitudes combining to give one overall signal.
- Frequency Domain: By applying the FFT (Fast Fourier Transform) algorithm to a Time Domain signal, it is converted to the Frequency Domain. In the Frequency Domain, each individual amplitude and frequency point is displayed.

Types of Vibration Surveys:
1. Overall Vibration: Outputs the sum of all vibration measured within a specified frequency range. Used as an initial “alarm” type survey, whereby if the overall indication is above a specified value, a more detailed survey is performed to identify the possible cause.

![Model 2020 ProBalancer Overall Vibration](image-url)
2. **Steady State**: Used to measure vibration at a constant engine/component operational frequency. Used to determine the speed / frequency at which balancing should be performed. It can also be used to identify critical operational conditions.

3. **Transient**: Data collected during a controlled change in the aircraft / component operational frequency. Often used in trending vibration over time by comparing surveys taken at specified intervals.

   **Peak Hold**: The maximum amplitude value measured is captured and held.

4. **Synchronous**: Utilizes a tachometer signal and a filter to track vibration of a specific rotor or shaft. The filter eliminates all vibrations above and below the tachometer signal input plus or minus the filter value. Used to determine the amplitude and phase (clock) angle of an imbalance condition.
Basic Balancing:
- Mass Imbalance
- Aerodynamic Imbalance

Fundamentals of Balancing

Data Collection and Processing:
- The vibration sensor is installed on the engine as near the front bearing as possible.
- The Photo tach is mounted on the cowling, behind the propeller.
- The reflective tape is applied to the back side of the target propeller blade in line with the Photo tach beam.
- The mass is located by the relative occurrence of tach trigger and mass passage at the radial sensor location.
- As the heavy spot on the propeller passes the location of the vibration sensor, the sensor generates and sends an electrical pulse to the analyzer.
- The Reflective tape triggers a response as it passes the Photo tach, which then sends an electrical signal to the analyzer.

In this illustration, the vibration sensor and Photo tach beam are co-located at the 12:00 or 0 degree position. Rotation is clock-wise from the viewer's position.
This is our starting point, elapsed time = 0

The speed is 1 RPM. Fifteen seconds (90 degrees) of travel has occurred. In this sequence, the reflective tape has just entered the Photo tach beam to trigger the tach event.
Elapsed time = 15 seconds.
The tape and mass have both passed the 0 degree location. The unit now waits for the exact sequence to repeat for averaging. Solution would be to add weight at 270 degrees.

The process is repeated while the analyzer averages out errors caused by momentary vibration events outside the running average.
Vibration Measurement

It is apparent that the intensity of vibration can be measured in terms of displacement, velocity, or acceleration. Acceleration is clearly the best parameter to measure at high frequencies. However, because displacements are large at low frequencies it would seem that measuring either displacement or velocity would be best at low frequencies. The amplitude of vibrations can be measured by various forms of displacement transducers. Fiber-optic-based devices are particularly attractive and can give measurement resolution as high as 1 mm. Unfortunately, there are considerable practical difficulties in mounting and calibrating displacement and velocity transducers and therefore they are rarely used. Because of this, vibration is usually measured by accelerometers at all frequencies. The most common type of transducer used is the piezoaccelerometer, which has typical inaccuracy levels of ±2%. The frequency response of accelerometers is particularly important in vibration measurement in view of the inherently high-frequency characteristics of the measurement situation. The bandwidth of both potentiometer-based accelerometers:

1- accelerometers using variable inductance-type displacement transducers only goes up to 25 Hz.
2- Accelerometers that include either the LVDT or strain gauges can measure frequencies up to 150 Hz.
3- the latest instruments using piezoresistive strain gauges have bandwidths up to 2 kHz.
4- Finally, inclusion of piezoelectric crystal displacement transducers yields an instrument with a bandwidth that can be as high as 7 kHz.

When measuring vibration, consideration must be given to the fact that attaching an accelerometer to the vibrating body will significantly affect the vibration characteristics if the body has a small mass. As well as an accelerometer, a vibration measurement system requires other elements to translate the accelerometer output into a recorded signal. The three other necessary elements are:

i. a signal conditioning element
ii. a signal analyzer
iii. a signal recorder.

The signal-conditioning element amplifies the relatively weak output signal from the accelerometer and also transforms the high output impedance of the accelerometer to a lower impedance value. The signal analyzer then converts the signal into the form required for output. The output parameter may be displacement, velocity, or acceleration, and this may be expressed as peak value, r.m.s. value, or average absolute value. The final element of the measurement system is the signal recorder. All
elements of the measurement system, especially the signal recorder, must be chosen very carefully to avoid distortion of the vibration waveform.

 Calibration of Vibration Sensors
 Calibration of the accelerometer used within a vibration measurement system is normally carried out by mounting the accelerometer in a back-to-back configuration with a reference calibrated accelerometer on an electromechanically excited vibrating table.
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Basic Vibration Sensors

1. Accelerometer Types of Accelerometers:
   • Charge mode
   • Piezoelectric
   • Internally amplified
   • Strain Gauge
   • Piezoresistive
   • Variable Capacitance

Advantages

➤ Very wide frequency range
➤ Rugged, industrial design

Disadvantages

➤ Not responsive to 0 Hz
➤ Internal Amplifier limits temperature range

Low Frequency Accelerometer Considerations:

➤ High Sensitivity
➤ Low Noise
➤ Low Pass Filter

Low Frequency Accelerometers:

➤ Measures Absolute Casing Motion
➤ Low Strain Sensitivity
➤ Overload Protected

Types of Accelerometers:

➤ Piezoelectric
➤ Strain Gauge

Piezoelectric Accelerometers:

➤ Measures Low Frequency
➤ Velocity or displacement output available

Advantages

➤ Measures Very Low Frequency
➤ Very Sensitive

Disadvantages

➤ Limited Amplitude Range
➤ Resists Thermal transients

Low Strain Accelerometer Considerations:

➤ Very Sensitive
➤ Contacting Measurements

Piezoelectric Accelerometers:

➤ Measures Acceleration

Disadvantages

➤ Measures Very High Frequency
➤ Limited Amplitude Range

Low Pass Filter

Environmental Protection

Resistor

Internal Amplifier

Amplifier

Seismic Mass

Stud

Base

Crystal

Connector

Mass
Piezoelectric Accelerometer - How It Works:

- Piezoelectric material (sensing element) is placed under load using a mass
- As ‘stack’ vibrates, crystal is squeezed or released
- Charge output is proportional to the force (and acceleration)
- Electronics convert charge output into voltage output

Metra offers accelerometers with three mechanical construction designs:
The reason for using different piezoelectric systems is their individual suitability for various measurement tasks and their varying sensitivity to environmental influences. The following table shows advantages and drawbacks of the three designs:

Shear:
- Low temperature transient sensitivity
- Low base strain sensitivity
- Lower sensitivity-to-mass ratio

Compression:
- High sensitivity-to-mass ratio
- Robustness
- Technological advantages
- High temperature transient sensitivity
- High base strain sensitivity

Bending:
- Best sensitivity-to-mass ratio
- Fragile
- Relatively high temperature transient sensitivity

The shear design is applied in the majority of modern accelerometers due to its better performance. Compression and bending type sensors are still used in many applications.
2. Non contacting Displacement Transducer

Eddy Current Probe Fabrication:

**How It Works**

- Three matched components - Driver, probe and extension cable
- Voltage applied to the Driver causes an RF signal to be generated
- Signal is transmitted to the probe by the extension cable
- Coil inside probe tip serves as an antenna and radiates high frequency energy into free space
- Any conductive material within the field absorbs energy and causes output of probe to decrease proportional to gap distance
3. Electrodynamics Velocity Transducer

Housing vibrates while the spring-suspended coil remains stationary.
Amplitude of the output voltage is proportional to the velocity of the vibration.

Advantages
➤ No external powering
➤ Powerful signal output
➤ Easy to use (not as sensitive to mounting problems as alternative)
➤ Ability to operate at elevated temperatures

Disadvantages
➤ Not useful for very low frequency
➤ Not useful for very high frequency
➤ Moving parts wear
➤ Mounting orientation may be important
➤ Size
➤ Accuracy (resolution / noise as compared to alternatives)
Machine damage in a power station

Rolling-element bearing damage
Vibration Measurement in the past (& still today):

Modern machine diagnosis

Measuring machine condition with a modern measuring Instrument
Measuring Absolute Bearing Vibration:

General rules:

- Measurement points should be exactly defined and clearly marked
- Measuring points should be flat, clean and free of grease
- Loose paint and rusted surfaces should be cleaned or avoided
- Sensor must sit securely and not wobble
- Sensor and cable should not move during measurement

Vibration velocity sensors

Measuring Relative Shaft Vibration:
Eddy-current sensors:

Discrete type:

- Sensor with integral cable
- Calibrated extension cable
- Separate converter (oscillator)
Acceleration sensors: