Vibration Analysis in Condition Monitoring and Fault Detection

Željko Kanović, Associated Professor
Automation and Control Systems Group
Faculty of Technical Sciences
University of Novi Sad, Serbia

Agenda

- Vibration Analysis Fundamentals
  - Basic definitions
  - Measured quantities
  - Vibration sensors
  - Vibration Analysis Techniques
- Condititon monitoring using vibration analysis
  - Overall vibration severity
  - Fault types and characteristic features
  - Application examples

Basic Definitions

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

Oscillation is the variation, usually with time, of the magnitude of a quantity with respect to a specified reference, when the magnitude is alternately greater and smaller than the reference

What causes vibrations?

- Excitation force – a force acting to the system and causing vibration response
- Types:
  - Harmonic

$$f(t) = F \cdot \sin(\omega t + \varphi_F)$$

F ... excitation force amplitude [N]

ω ... excitation force angular frequency [rad/s]

t ... time [s]

φ_F ... excitation force initial phase shift,

  - Harmonic vibrations

$$x(t) = X \cdot \sin(\omega t + \varphi_F - \varphi)$$

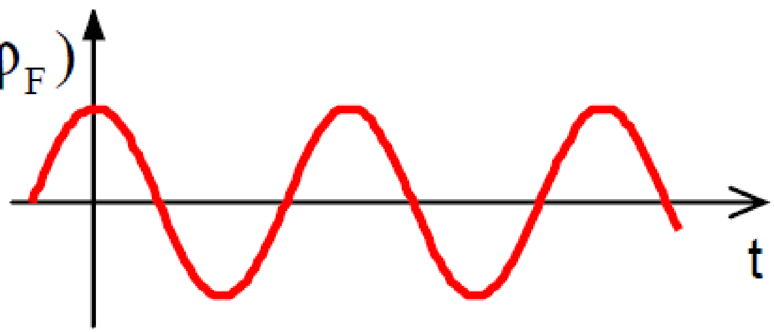
X ... amplitude of forced vibration

φ ... phase shift - lag between the displacement and the acting force

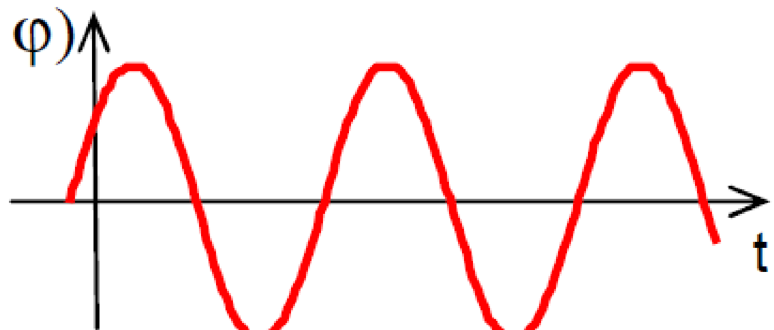
What causes vibrations?

- Excitation force – a force acting to the system and causing vibration response
- Types:
  - Harmonic

$$f(t) = F \cdot \sin(\omega t + \varphi_F)$$

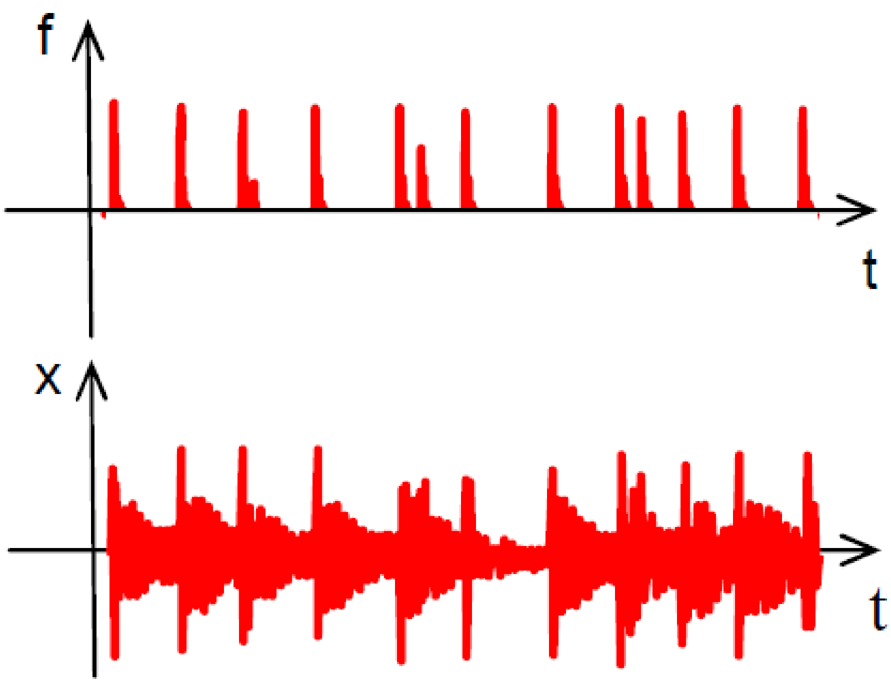


$$x(t) = X \cdot \sin(\omega t + \varphi_F - \varphi)$$



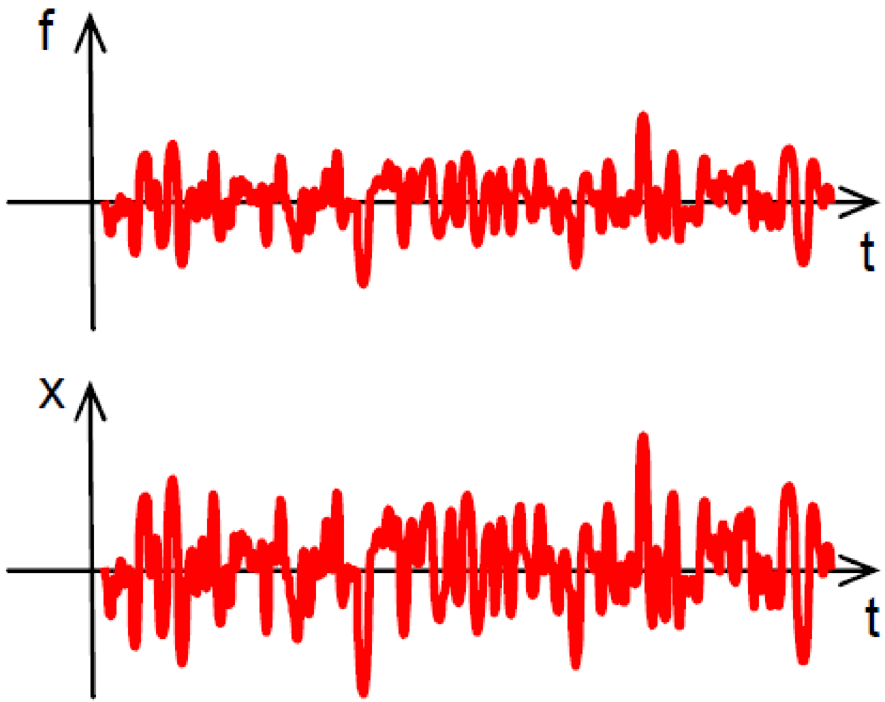
What causes vibrations?

- Excitation force – a force acting to the system and causing vibration response
- Types:
  - Impulse – impact excitation (can also be periodic)



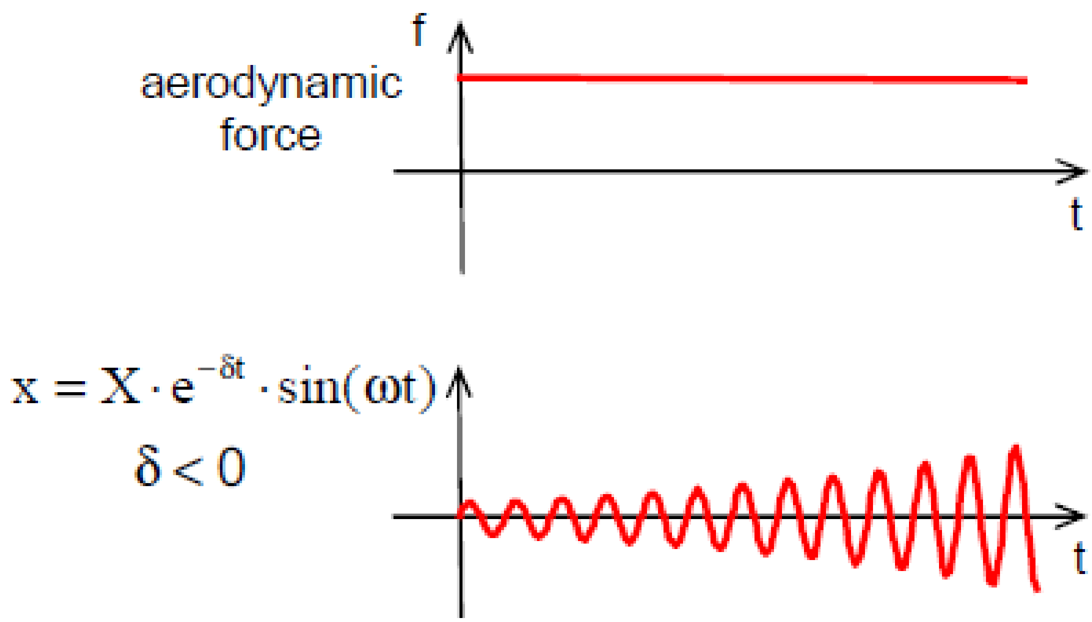
What causes vibrations?

- Excitation force – a force acting to the system and causing vibration response
- Types:
  - Random



What causes vibrations?

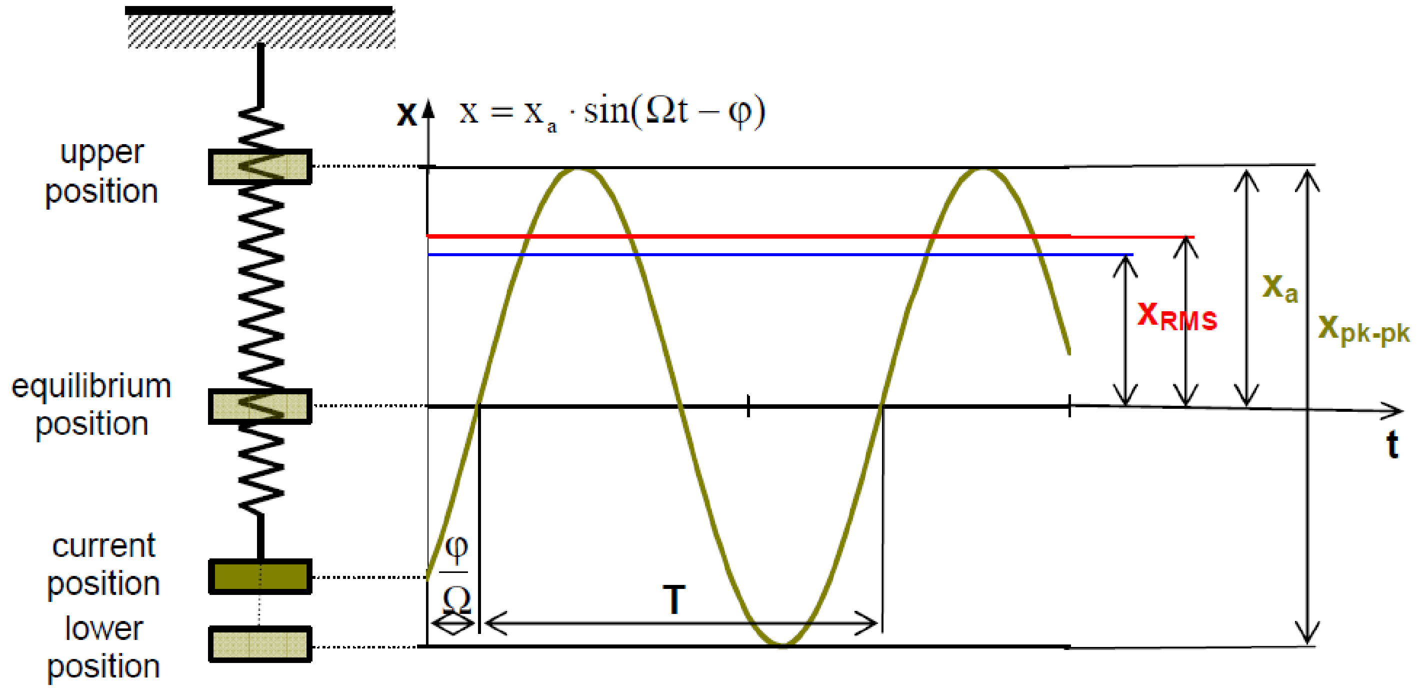
- Excitation force – a force acting to the system and causing vibration response
- Types:
  - Self-excited vibrations – MUST be controlled or avoided



What causes vibrations?

- Excitation force – a force acting to the system and causing vibration response
- Types:
  - Self-excited vibrations – MUST be controlled or avoided

Basic quantities



$$x(t) = x_a \cdot \sin(\Omega t - \varphi)$$

x_a ... amplitude of harmonic oscillation [m]

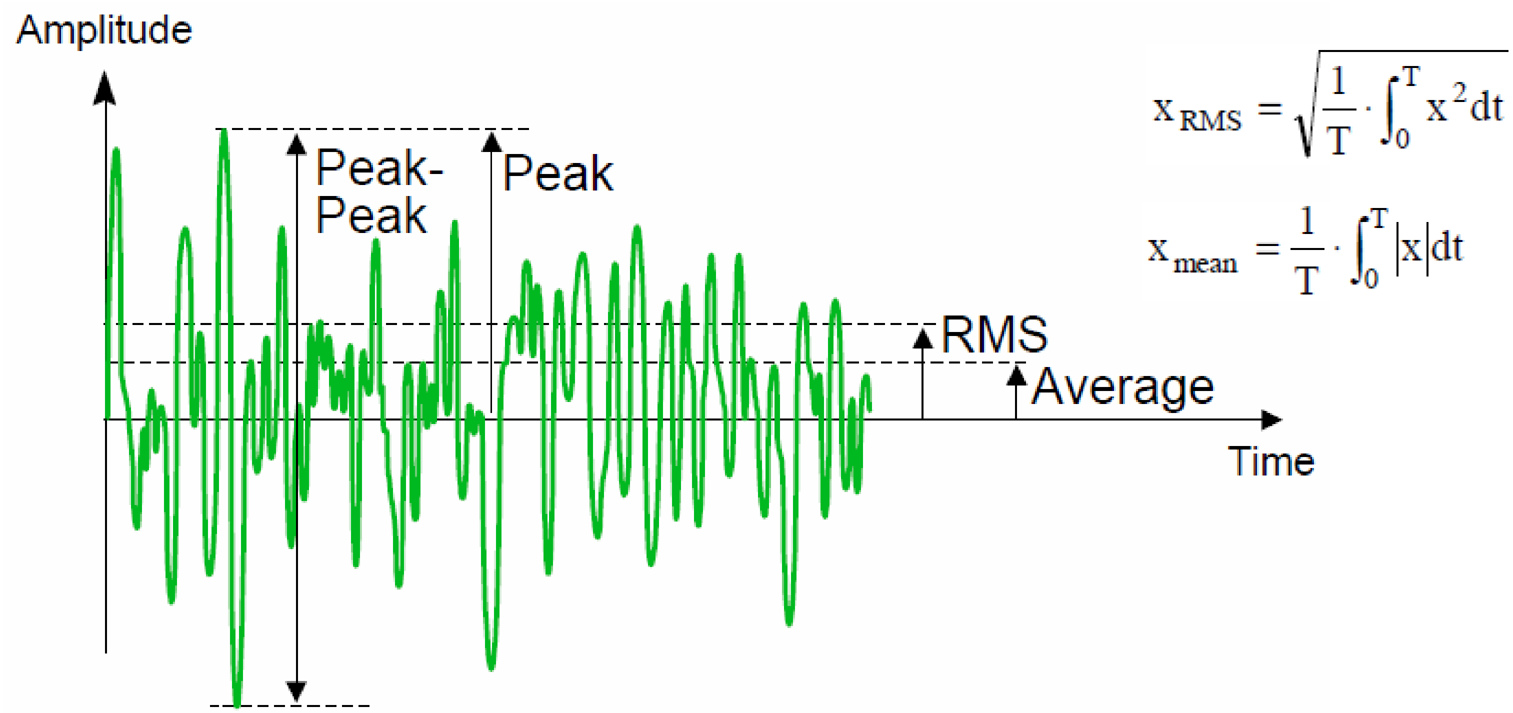
Ω or ω angular natural frequency [rad/s]

φ ... initial phase shift (is determined by the initial displacement)

$$f = \frac{\omega}{2\pi} \quad [\mathrm{Hz}]$$

$$T = \frac{1}{f} = \frac{2\pi}{\omega} \quad [\mathrm{s}]$$

Basic quantities



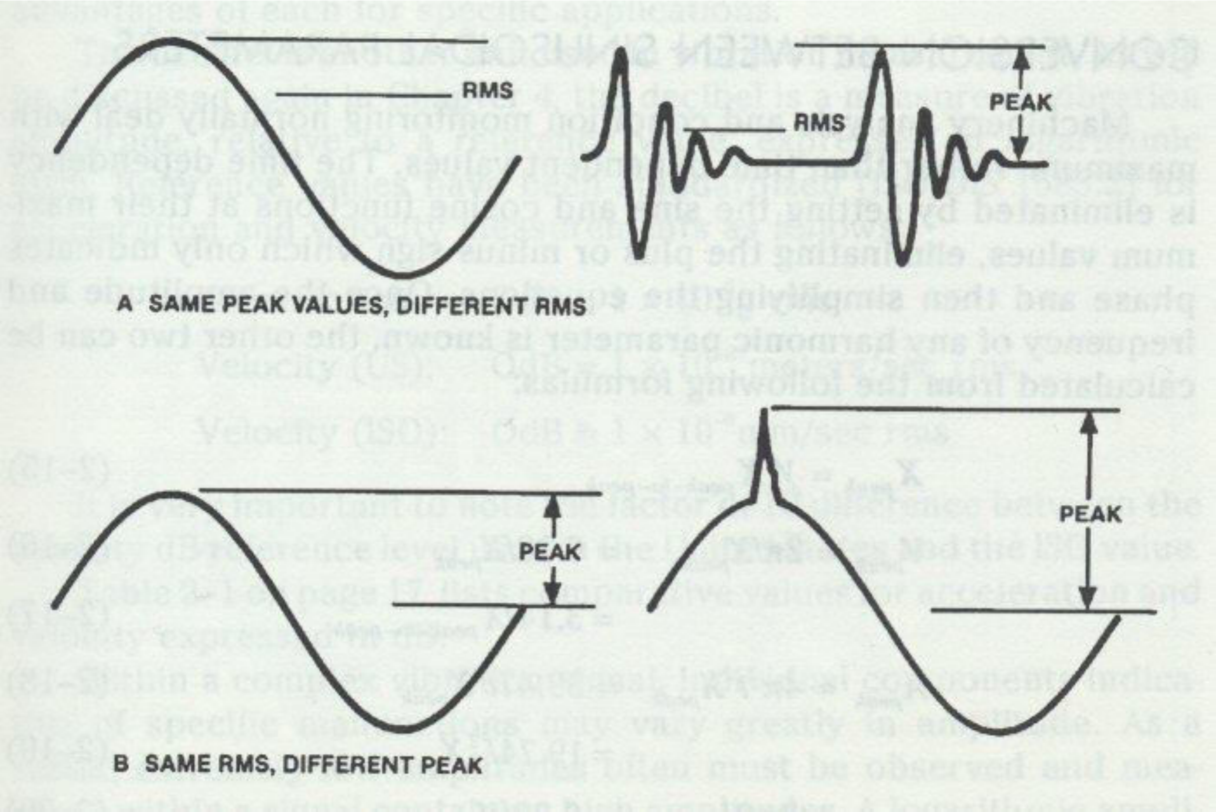
Peak to Peak - the distance from the top of the positive peak to bottom of the negative peak.

Peak - the measurement from the zero line to the top of the positive peak.

Average *(AVG)* - .637 of peak.

Root Mean Square *(RMS)* - .707 of peak.

Illustration



These parameters have a direct impact on the measurement value. If the wrong parameter is used, the measurement could be either too high, or too low, thus causing possible maintenance action to be accomplished erroneously.

Measured quantities

- Amplitude is an indicator of the severity of a vibration. Amplitude can be expressed as one of the following engineering units:
  - ☒Displacement
  - ☒Velocity
  - ☒Acceleration

Displacement

- Displacement is a measure of the actual distance an object is moving from a reference point.
- Displacement is usually expressed in microns (1 micron = 10^{-6} m), or “mils” (1 mil = .001 inch)

Velocity

- Velocity is the rate of change in position
- First derivative of displacement with respect to time
- Typical velocity units are **mm/s** (millimeters per second) and **IPS** (Inches Per Second)

Acceleration

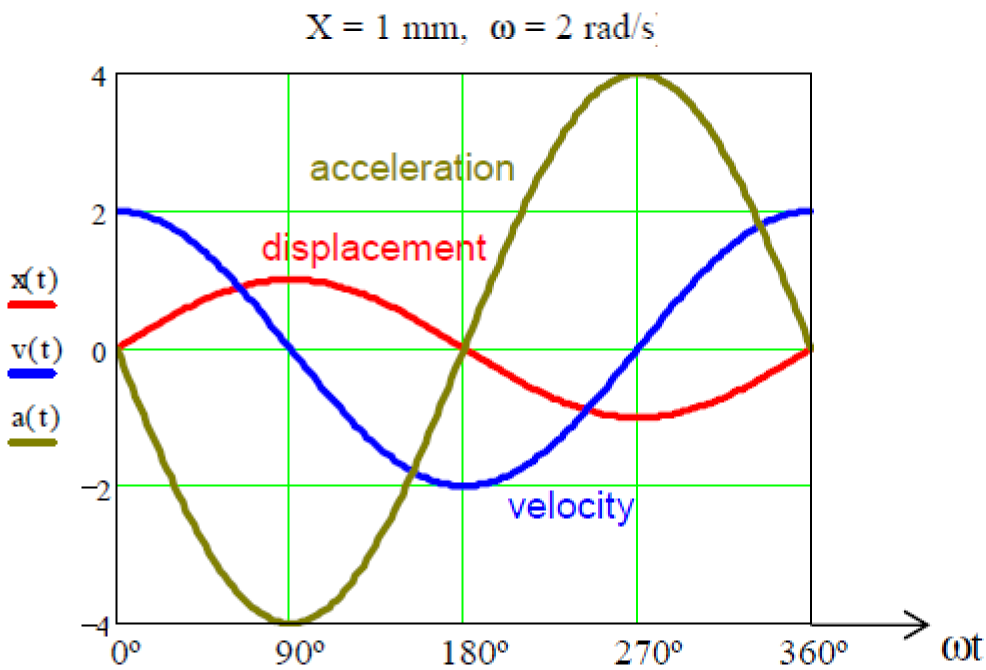
- Acceleration is the rate of change of velocity and is the measurement of the force being produced.
- Second derivative of displacement with respect to time
- Acceleration is expressed in m/sec^2 or in gravitational forces - “g’s”, ($1g = 9.81\ m/sec^2$)

Relation

$$x(t) = X \cdot \sin(\omega t)$$

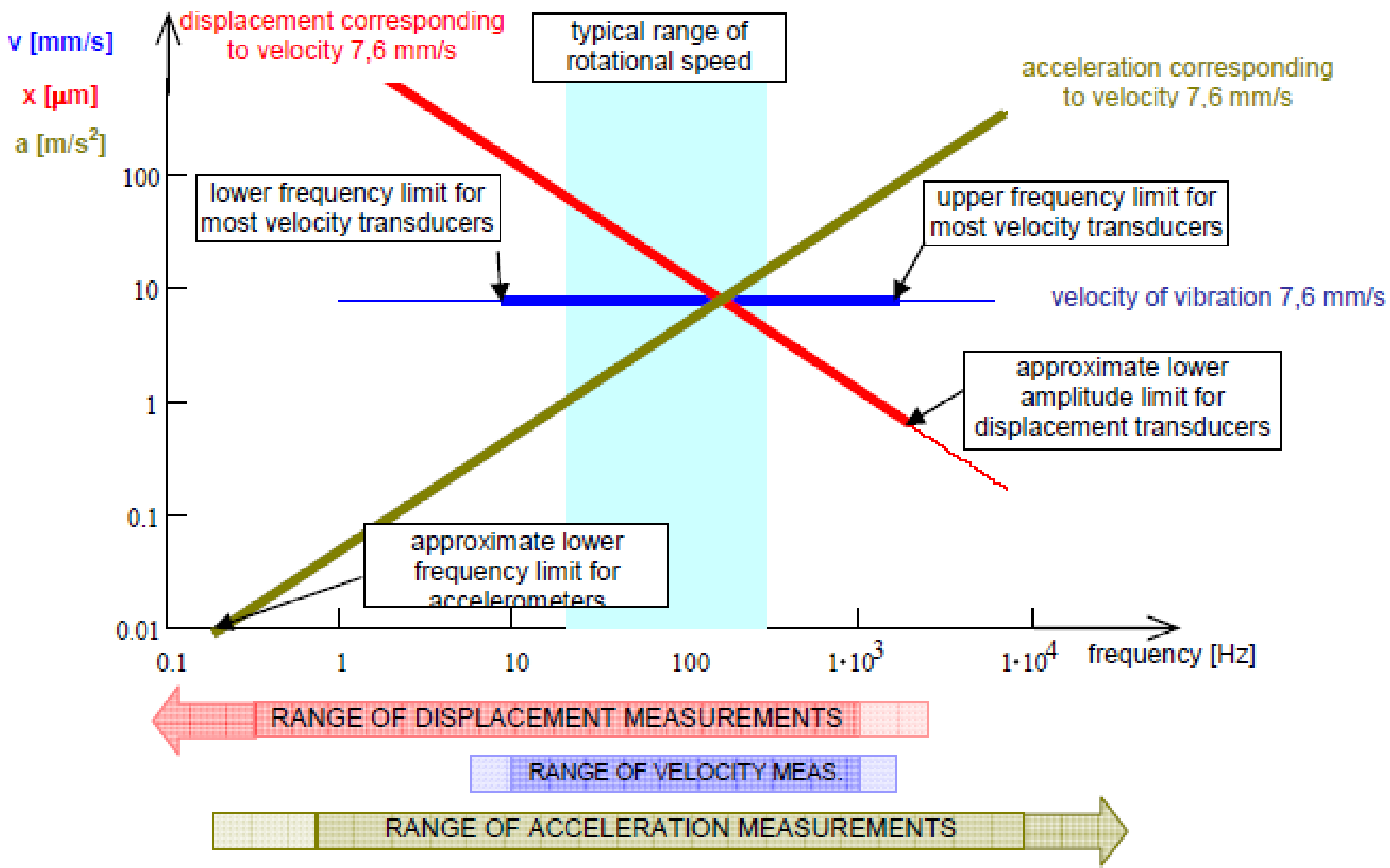
$$v(t) = \frac{dx}{dt} = X \cdot \omega \cdot \cos(\omega t)$$

$$a(t) = \frac{dv}{dt} = -X \cdot \omega^2 \cdot \sin(\omega t)$$



- Theoretically, one parameter is sufficient to calculate other two!
- In practice, it is always the best if we can measure the quantity we observe (due to noise, measurement errors...)

Relation



- Measured quantity depends mostly on frequency range of interest!

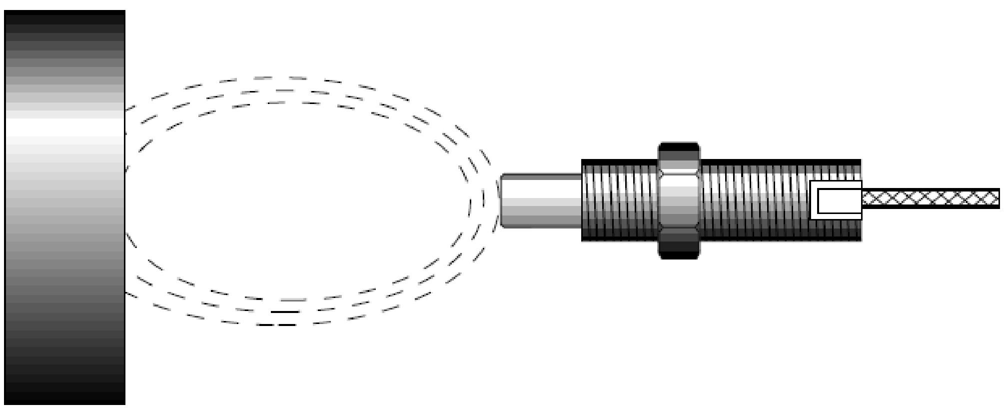
Vibration sensors

- A transducer that converts mechanical motion into electronic signals.
- Three categories:
  - Displacement
  - Velocity
  - Accelerometer
- Different frequency response and dynamic range

Sensor Type

Displacement

- Measures the distance an object is moving from a reference position.
- How it Works: The tip of the probe contains an encapsulated wire coil which radiates the driver's high frequency (about 1.5MHz) as a magnetic field. When a conductive surface comes into close proximity to the probe tip, eddy currents are generated on the target surface decreasing the magnetic field strength, leading to a decrease in the driver's DC output.



- Most accurate in frequencies below 10 Hz, or 600 RPM
- Common sensitivity 8mV/μm

Sensor Type

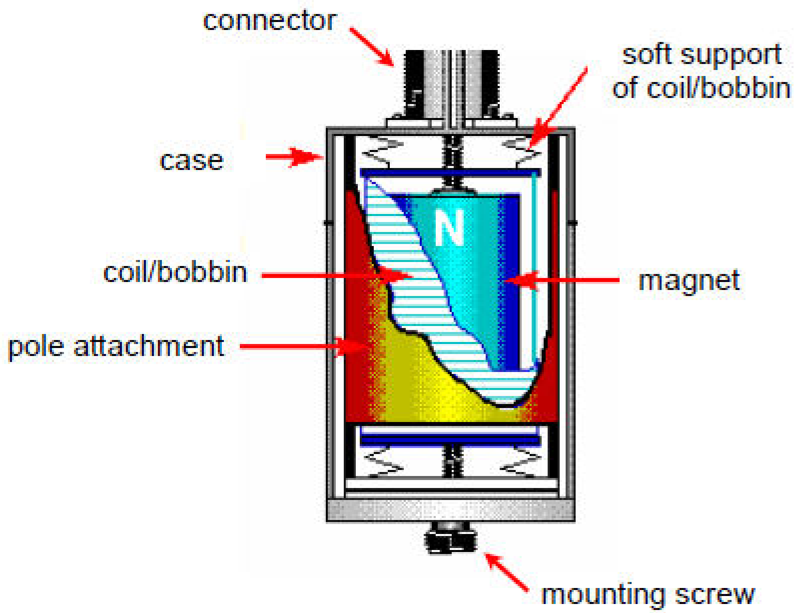
Displacement

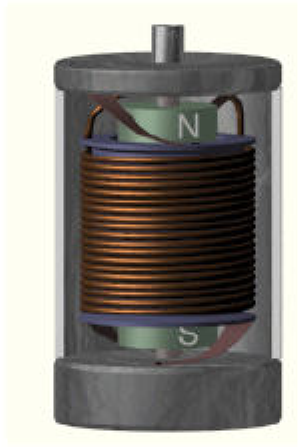
- Pro’s and Con’s
  - Pro’s
    - Measures Displacement
    - Rugged
  - Con’s
    - Limited Frequency Range (up to max.1000Hz, usually up to 10Hz)
    - Susceptible to electrical or mechanical runout
    - Linear only in a small range (0.25 to 2.3 mm)
    - Installation Issues

Sensor Type

Velocity

- Measures the rate of change of position an object is moving.
- A permanent magnet, attached to the vibrating object, moving back and forth within a coil winding induces an *emf* in the winding, proportional to the velocity of oscillation of the magnet.





- Best suited to measure vibrations between ~ 10 Hz and 1000 Hz (max. 1500Hz)

Sensor Type

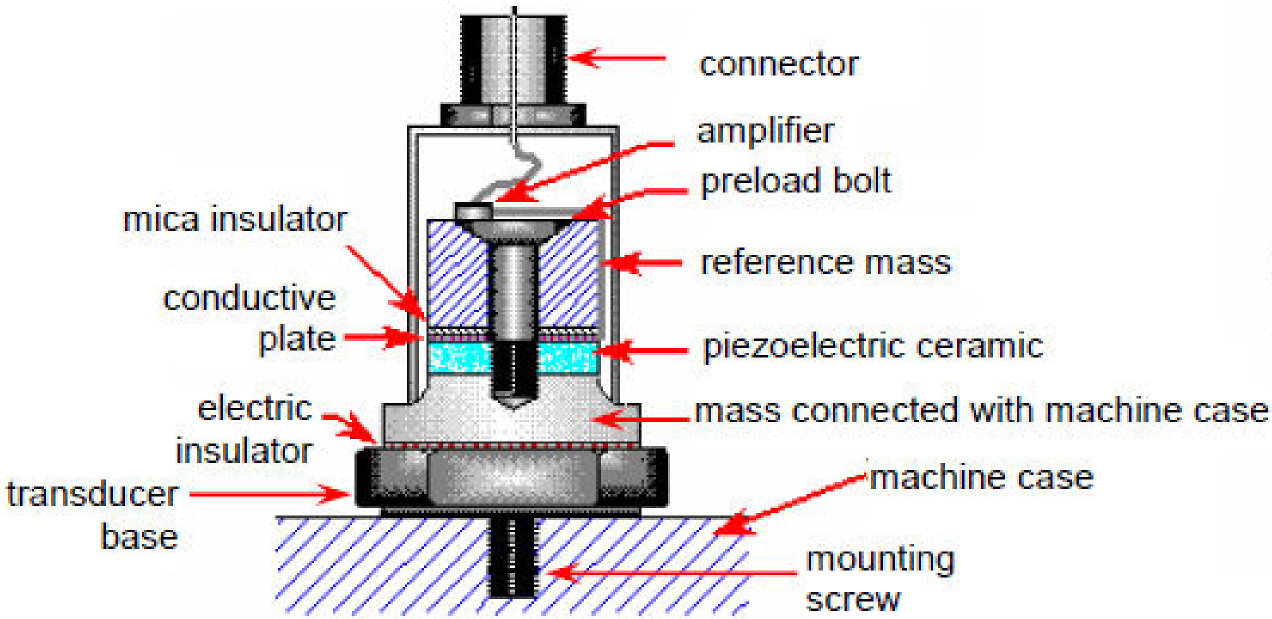
Velocity

- Pro’s and Con’s
  - Pro’s
    - Measures Velocity
    - Low-cost and quite sensitive
    - Easier Installation than Displacement
  - Con’s
    - Limited Frequency Range (10-1000Hz)
    - Susceptible to Shocks and Calibration Problems
    - Very sensitive to cable damage
    - Large Size
    - Only for Permanent Mounting

Sensor Type

Accelerometer

- Measures the rate of change of velocity per time period. Acceleration is mostly reported in g's.

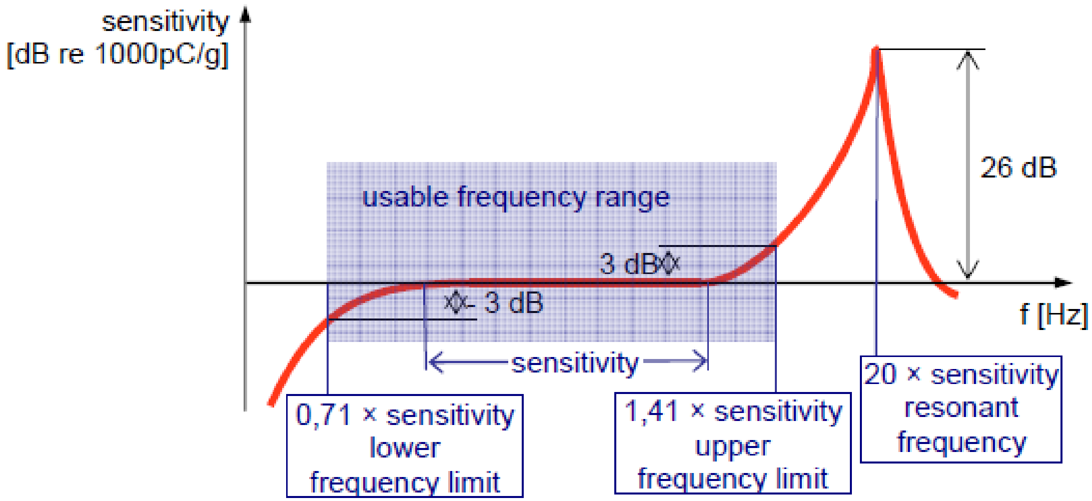


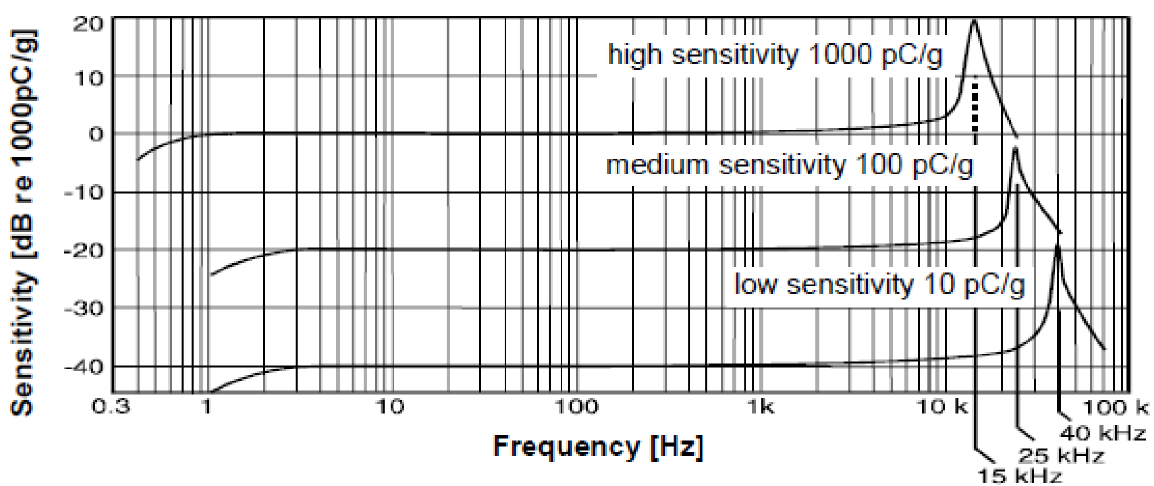
- Most effective frequency range for an accelerometer is above 100 Hz, or 6000 RPM.
- 1, 2 or 3 axis

Sensor Type

Accelerometer

- Must be calibrated.





Sensor Type

Accelerometer

- Pro's and Con's
  - Pro's
    - Measures Acceleration
    - Small Size
    - Easily Installed
    - Large Frequency Range (1-10,000 Hz)
  - Con's
    - Measures Acceleration (requires Integration to Vel.)
    - Susceptible to Shock & Requires Power
    - Only for absolute vibration

Sensor Selection

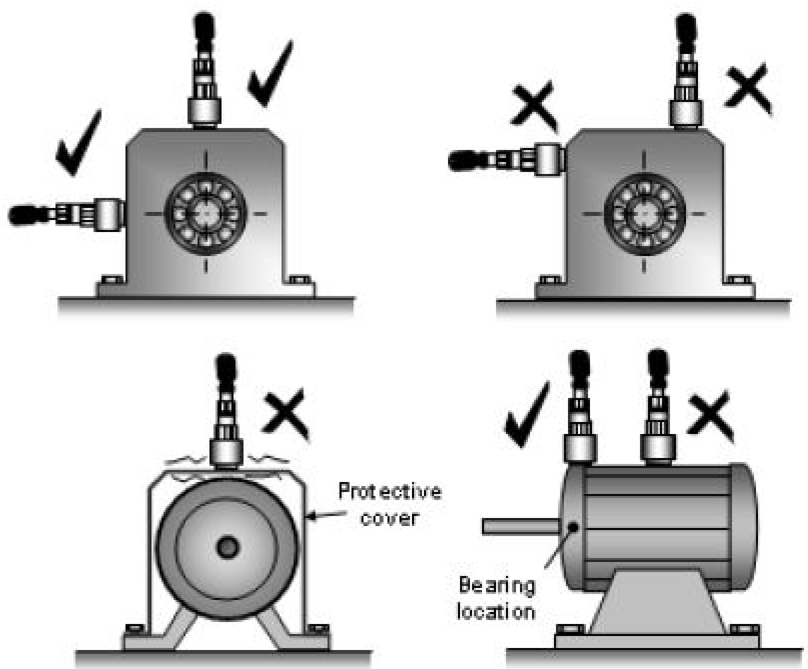
- The first consideration is manufacturer's recommendations. If none exist, then:
  - Frequency Range
  - Environmental conditions

Sensor Installation

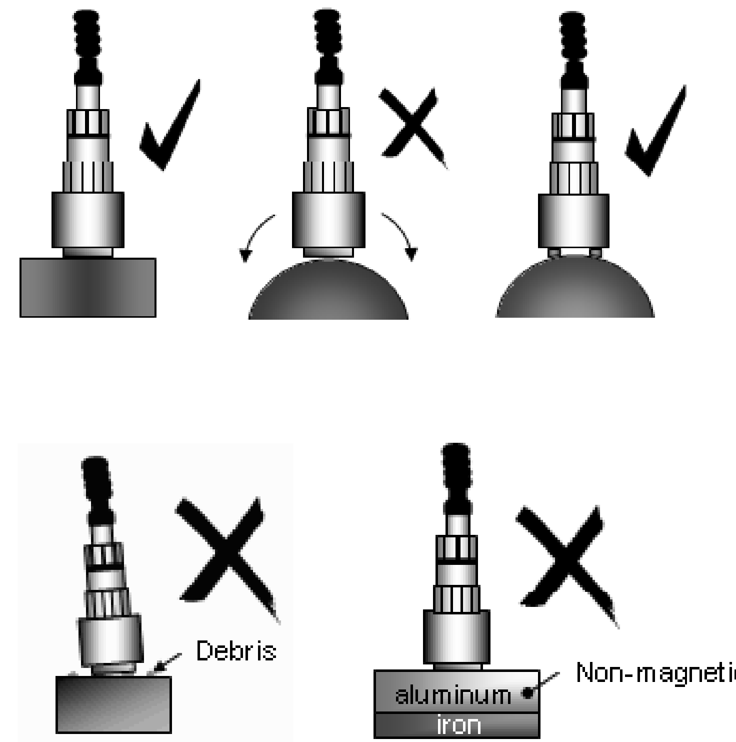
- Varies depending upon the application.
- Most manufacturers provide the specific location for mounting and this should be strictly adhered to. If these recommendations are not followed, the resulting measurements may be invalid.
- Mountings:
  - Permanent (casted or welded sensor housing, glue, …)
  - Temporary (thread, magnetic,adhesive tape, beeswax …)
- Generally, mount in a location that provides the closest proximity to the component of interest.

Sensor Installation

- Close to vibration source

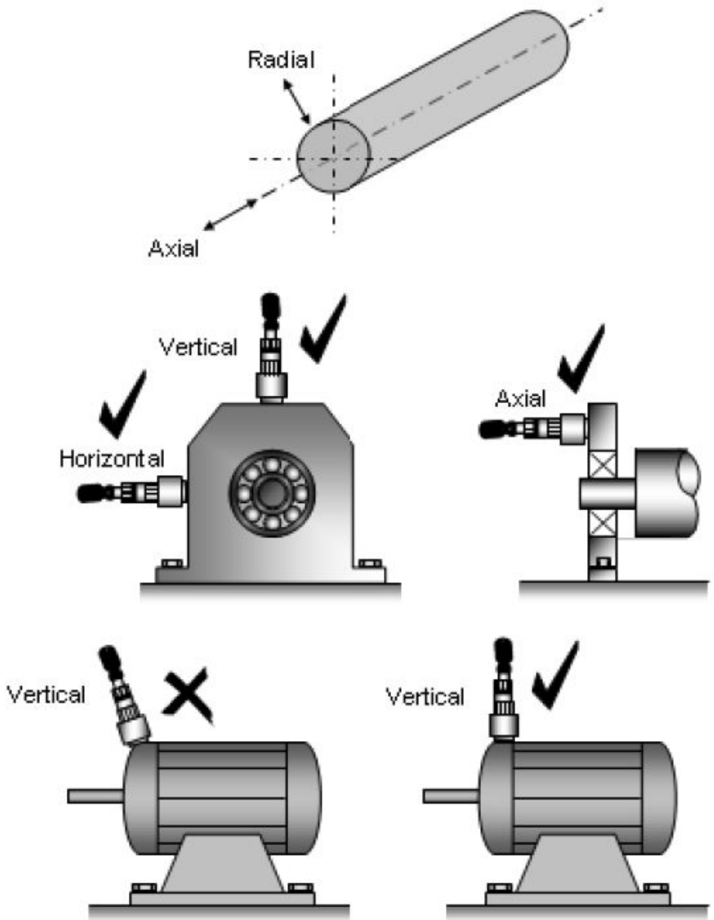


- Firmly attached

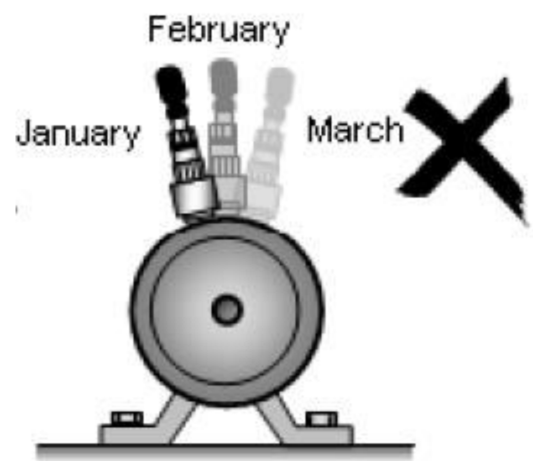


Sensor Installation

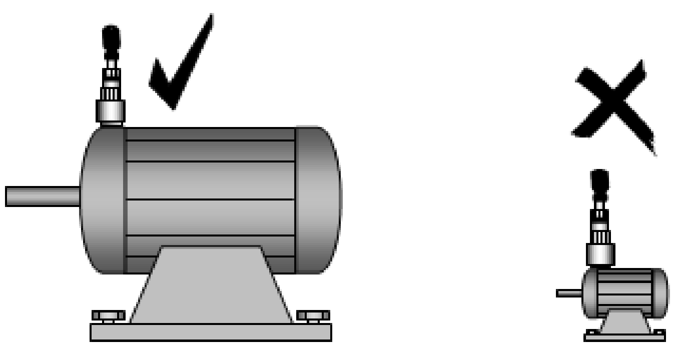
- Correctly oriented



- Always at the same location

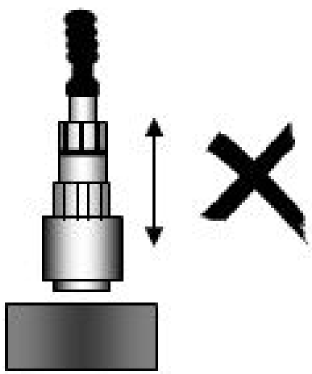


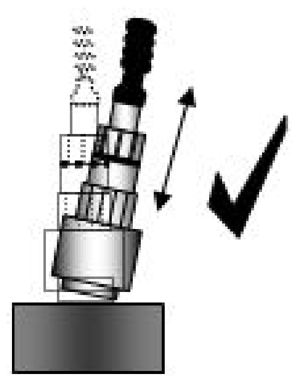
- On something substantial

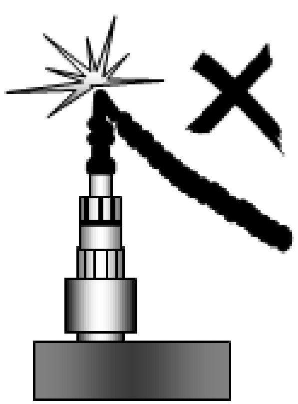


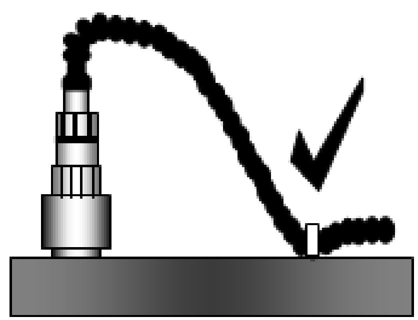
Sensor Installation

- Take care of sensor

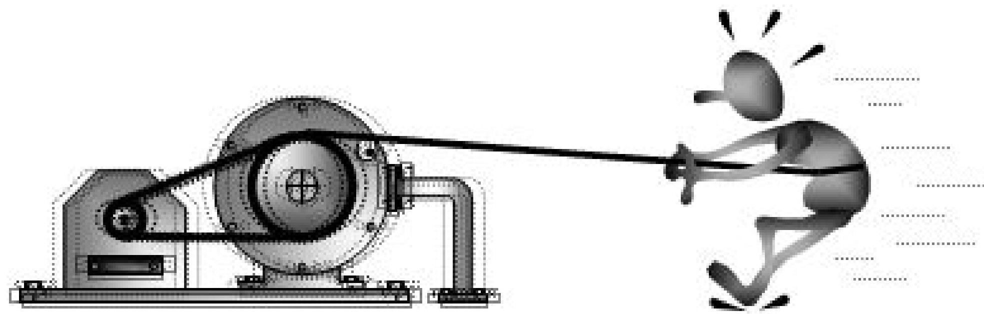






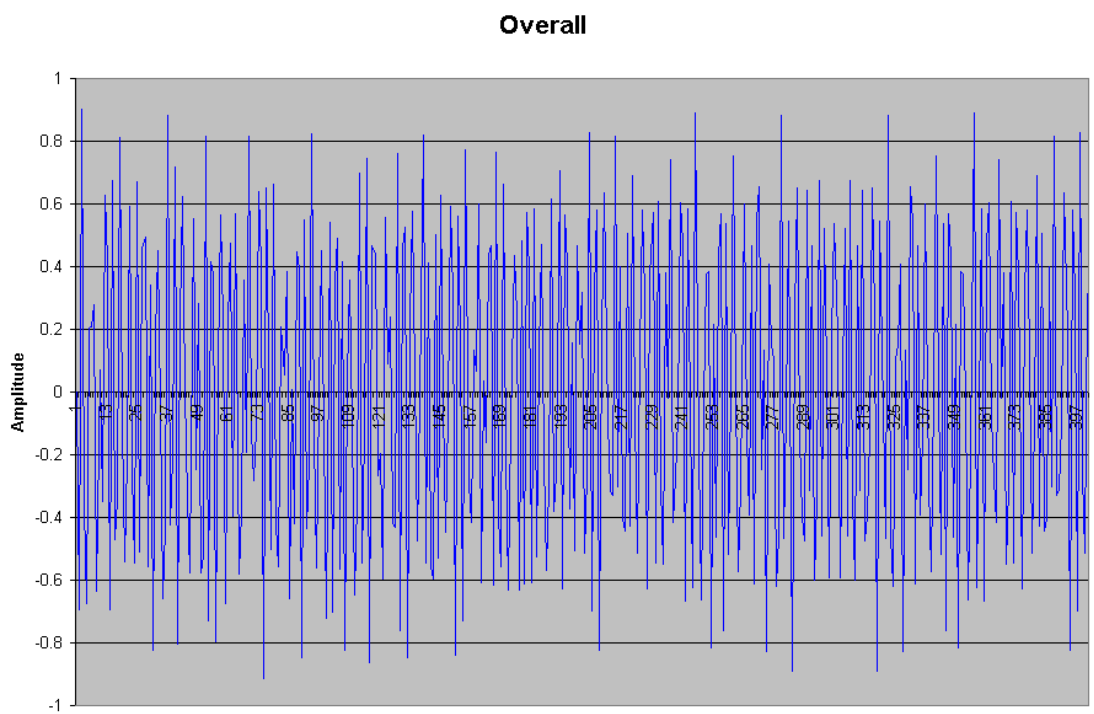


- **Take care of personal safety!!!**



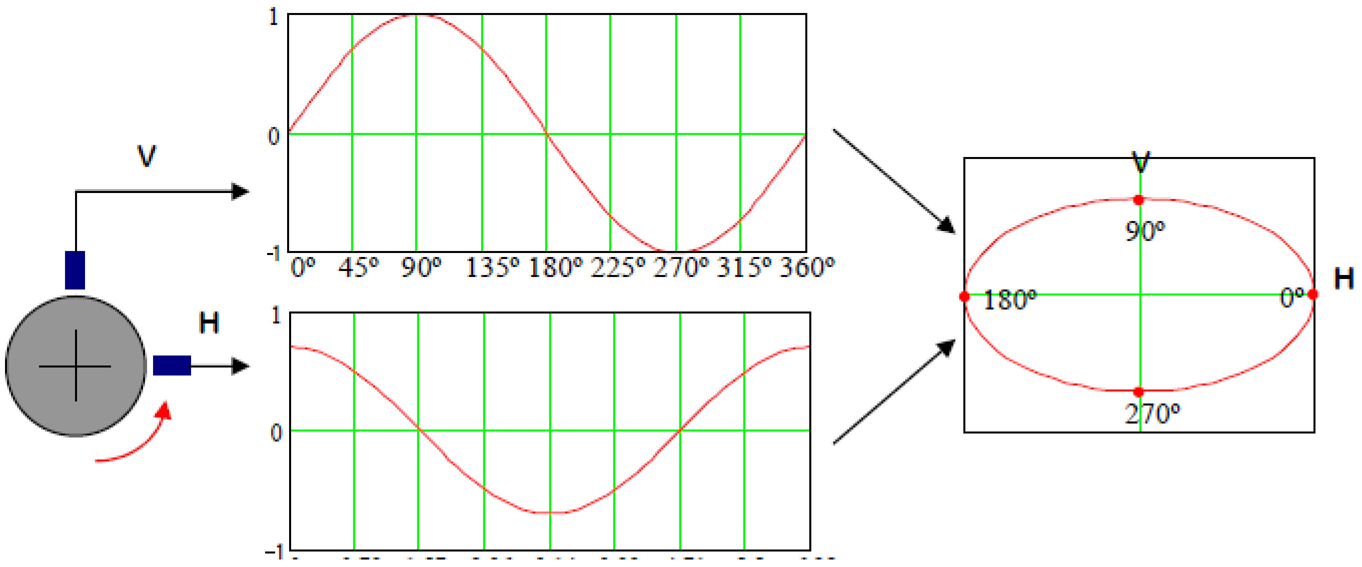
How Vibration Is Analyzed

- Time Domain - Vibration vs. Time.
  - A vibration signal is presented as a sine wave form with all frequencies and amplitudes combining to give one overall signal.



How Vibration Is Analyzed

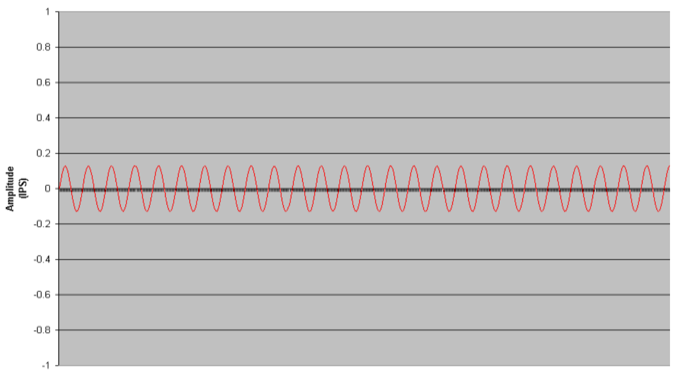
- Time Domain - Vibration vs. Time.
  - Special case when displacement is measured – Orbit Plot



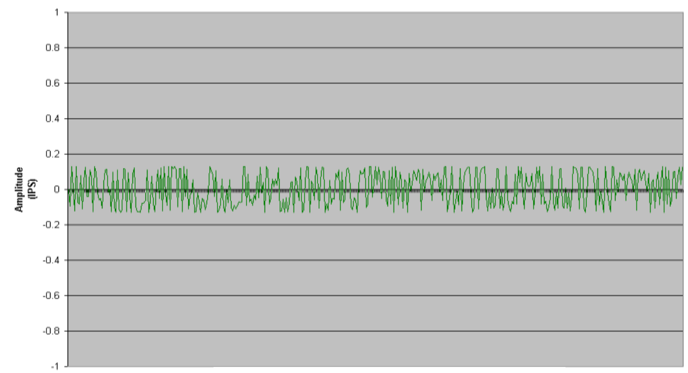
How Vibration Is Analyzed

- Time Domain - Vibration vs. Time.
  - This would be difficult to use as a means of determining vibration faults in mechanical structure.

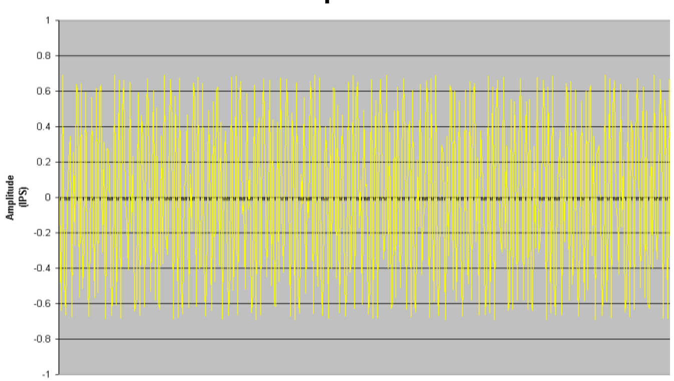
Component 1



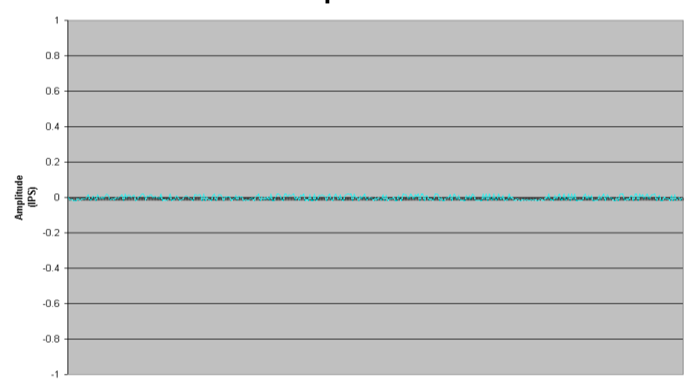
Component 2



Component 3

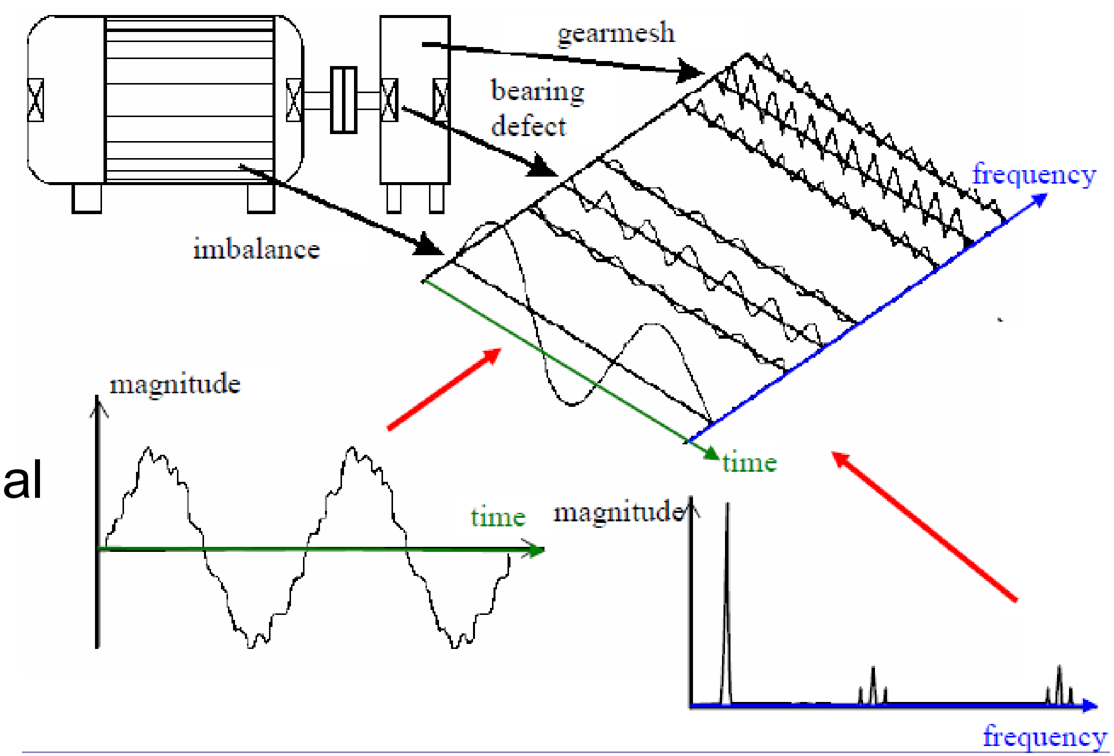


Component 4



How Vibration Is Analyzed

- Frequency Domain
  - By applying the FFT (Fast Fourier Transform), Time Domain signal is converted to the Frequency Domain.
  - In the Frequency Domain, each individual amplitude and frequency point are displayed.



How Vibration Is Analyzed

- Fourier transform
  - Periodical function x(t) can be expressed as:

$$x(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty}\left[a_n \cdot \cos(n\omega t) + b_n \cdot \sin(n\omega t)\right] \quad ; \quad \omega = \frac{2\pi}{T}$$

  - Fourier (spectral) coefficients

$$a_n = \frac{2}{T} \cdot \int_0^T x(t) \cdot \cos(n\omega t)\,dt \qquad b_n = \frac{2}{T} \cdot \int_0^T x(t) \cdot \sin(n\omega t)\,dt$$

  - Discretization

$$x_k\left(= x(t_k)\right) = \frac{a_0}{2} + \sum_{n=1}^{N/2}\left(a_n \cdot \cos\left(\frac{2\pi n t_k}{T}\right) + b_n \cdot \sin\left(\frac{2\pi n t_k}{T}\right)\right) \; ; \; k = 1, N$$

$$c_n\left(= X_n\right) = \sqrt{a_n^2 + b_n^2} \qquad \phi_n = \operatorname{arctg}\left(-\frac{b_n}{a_n}\right)$$

Amplitude

Phase

acs automation and control systems group

How Vibration Is Analyzed

- Fourier transform
  - Discrete Fourier Transform (DFT)

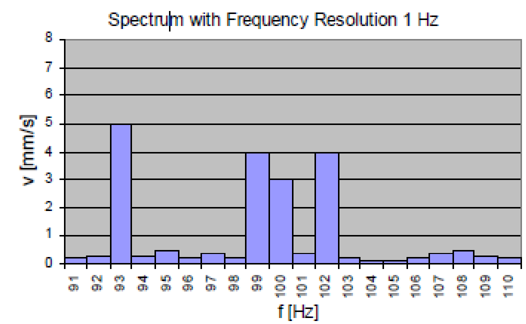
$$x_k\left(=x(t_k)\right)=\frac{a_0}{2}+\sum_{n=1}^{N/2}\left(c_n\cdot\cos\left(\frac{2\pi n t_k}{T}+\varphi_n\right)\right)$$

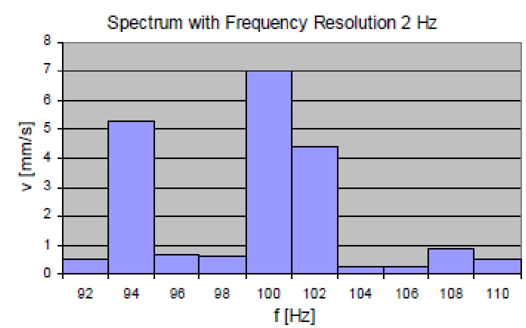
  - Frequency range:

$$f_{max}=\frac{f_s}{2}=\frac{1}{2}\cdot\frac{N}{T}$$ Nyquist frequency

  - Spectral resolution:

$$\Delta f=\frac{1}{T}=\frac{f_S}{N}$$

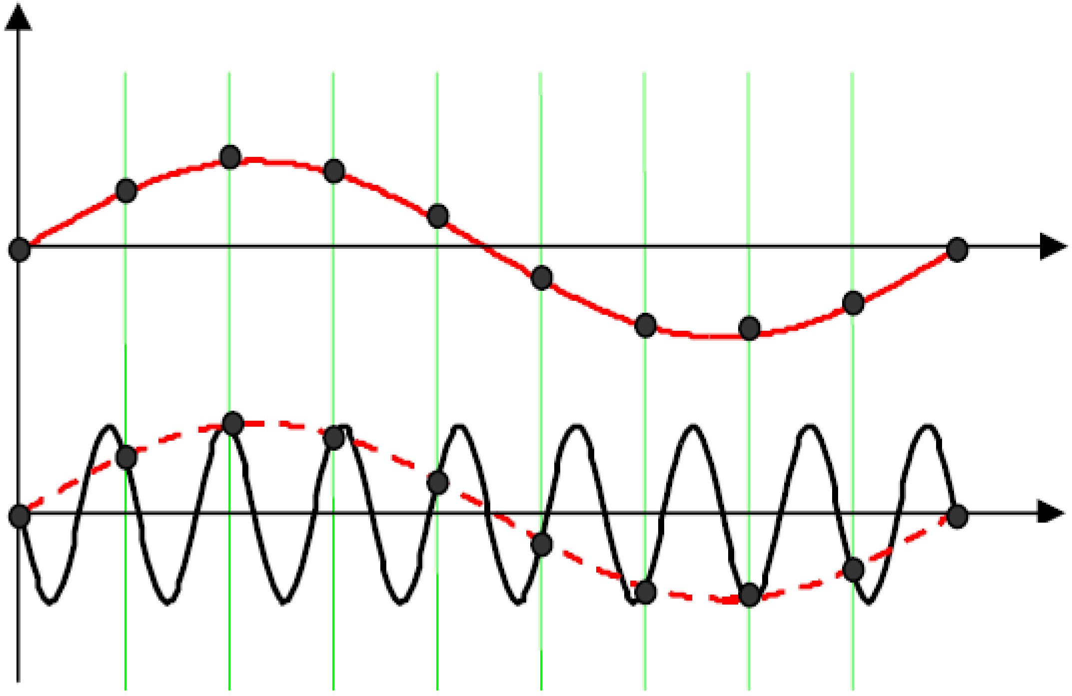




  - Fast Fourier Transformation (FFT) – N integer power of 2; most common algorithm used in practice

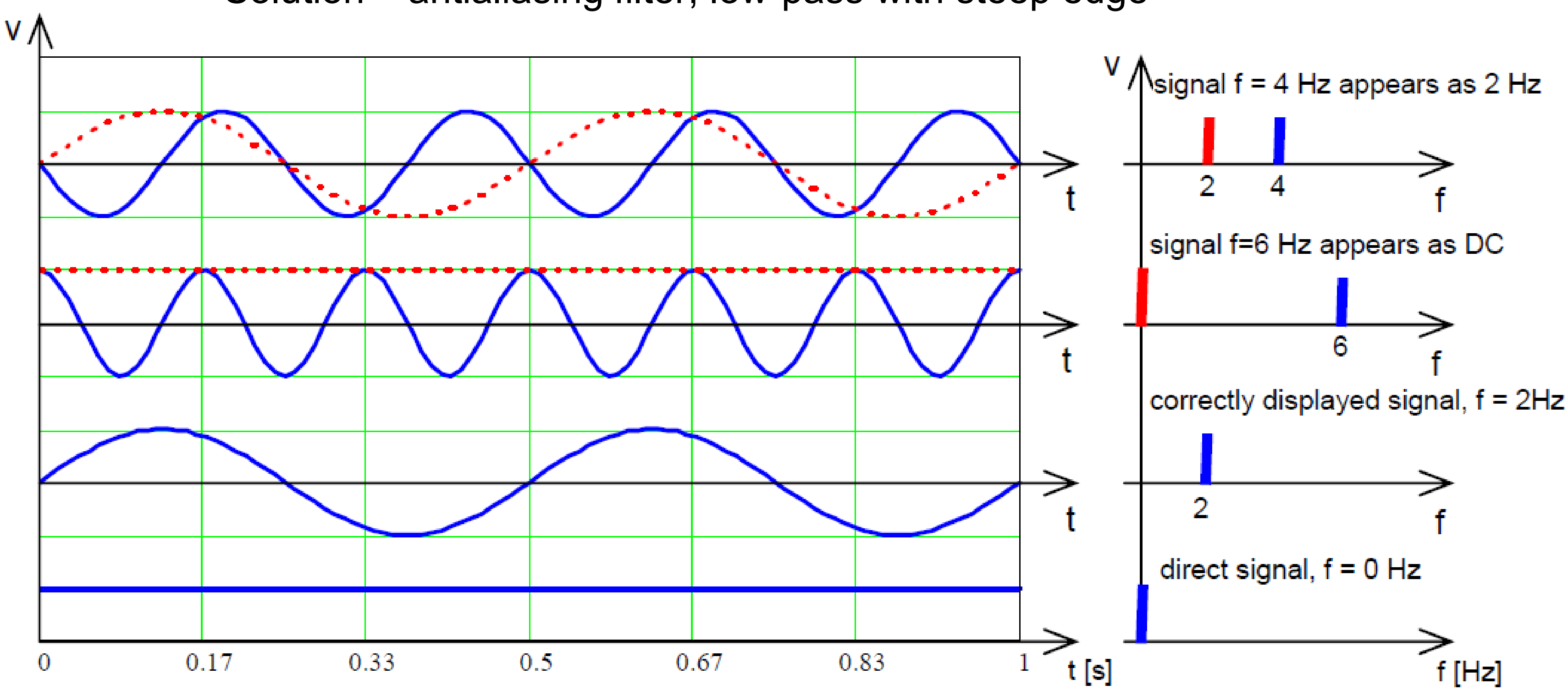
How Vibration Is Analyzed

- Fourier transform
  - Problems
    - Aliasing error (Stroboscopic effect) – sampling frequency too low
    - In practice: $f_s = 2.56 \times f_{max}$



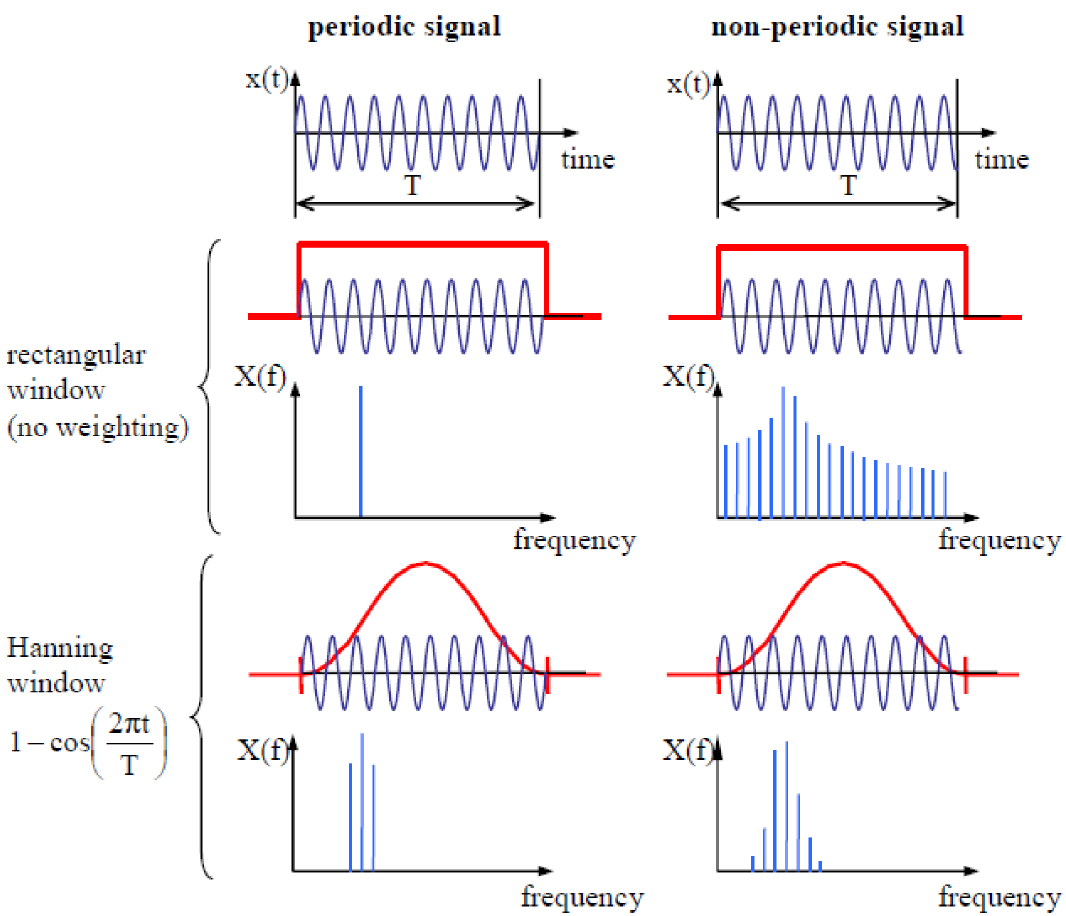
How Vibration Is Analyzed

- Fourier transform
  - Problems
    - Aliasing error (Stroboscopic effect) – sampling frequency too low
    - In practice: $f_s = 2.56 \times f_{max}$
    - Solution – antialiasing filter, low-pass with steep edge



How Vibration Is Analyzed

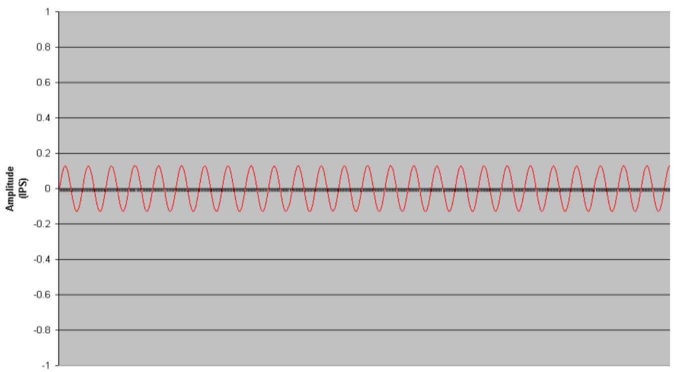
- Fourier transform
  - Problems
    - Leakage error – if function is not periodic
    - Solution - windowing



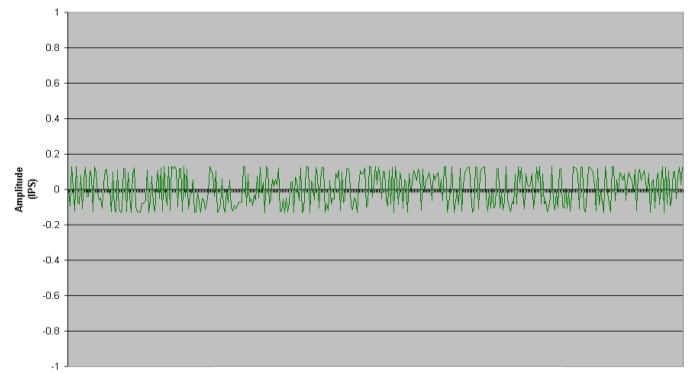
How Vibration Is Analyzed

- Frequency Domain

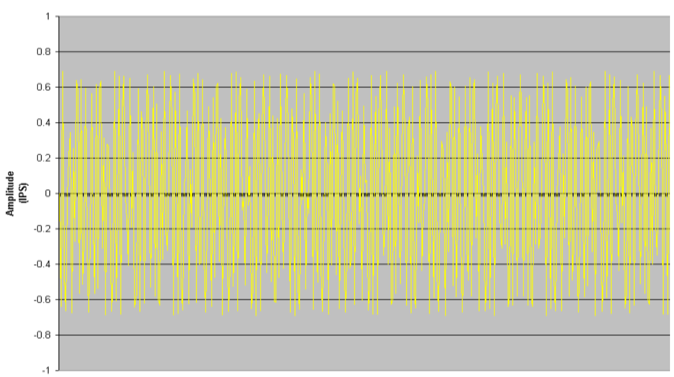
Component 1



Component 2



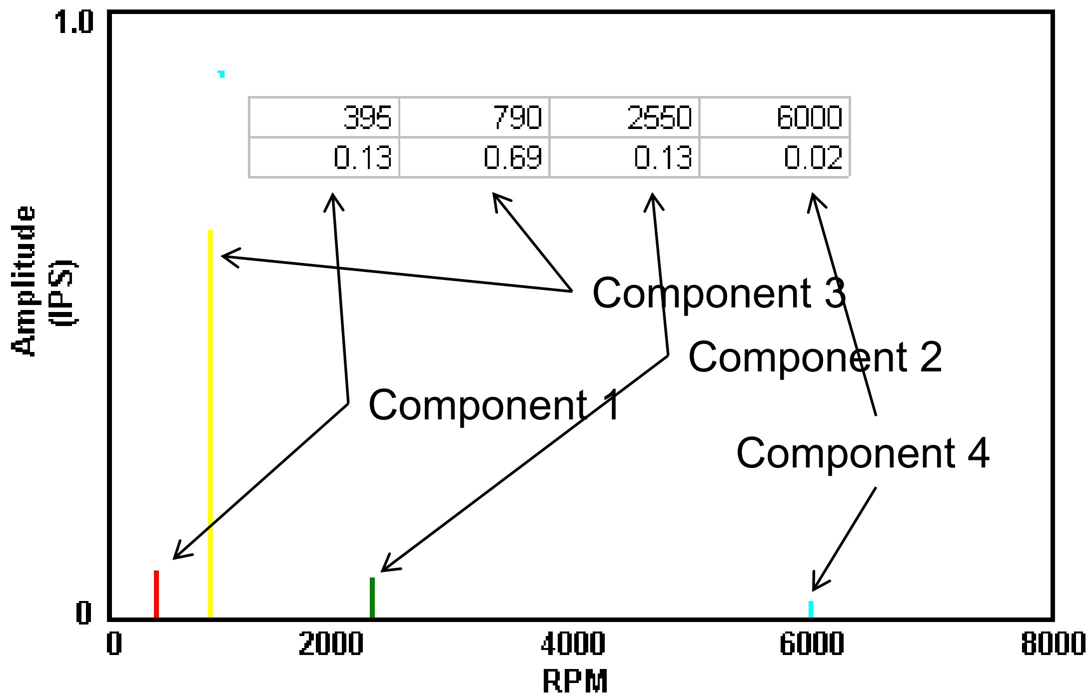
Component 3



Component 4

How Vibration Is Analyzed

- Frequency Domain



Condition Monitoring and Fault Detection of Induction Motors

- Prevents unplanned maintenance
- Maintenance types:
  - Preventive, periodical
  - Predicitive
  - Proactive
- Benefits:
  - Real-time indication of overall system condition
  - Reduction of critical components failure likelihood
  - Maintenance cost, spare parts and personnel requirements reduction
  - Safety and reliability improvement

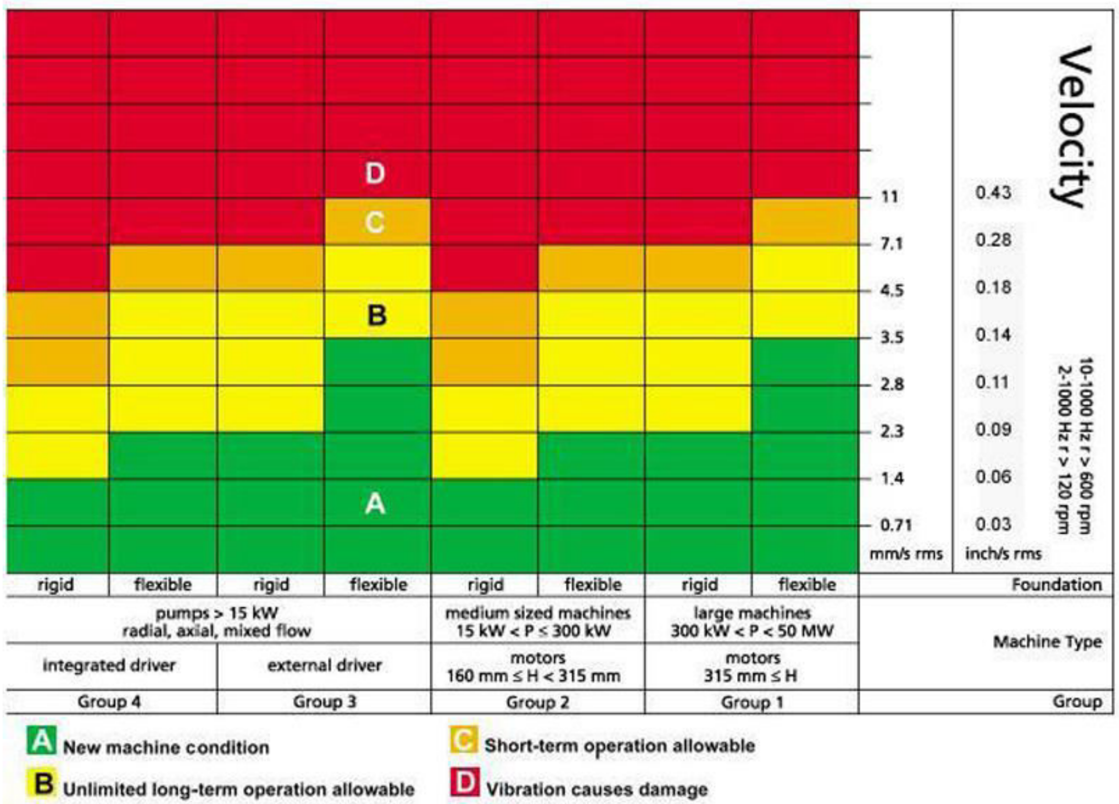
Condition Monitoring and Fault Detection of Induction Motors

- Generally, two approaches:
- Monitoring of overall vibration level
  - Defined in ISO 10816
  - Vibration magnitude and change in vibration magnitude
  - Determines general condition, not particular faults

- Frequency analysis with characteristic features extraction
  - Based on frequency analysis techniques
  - Fault diagnosis is possible
  - Not standardized yet

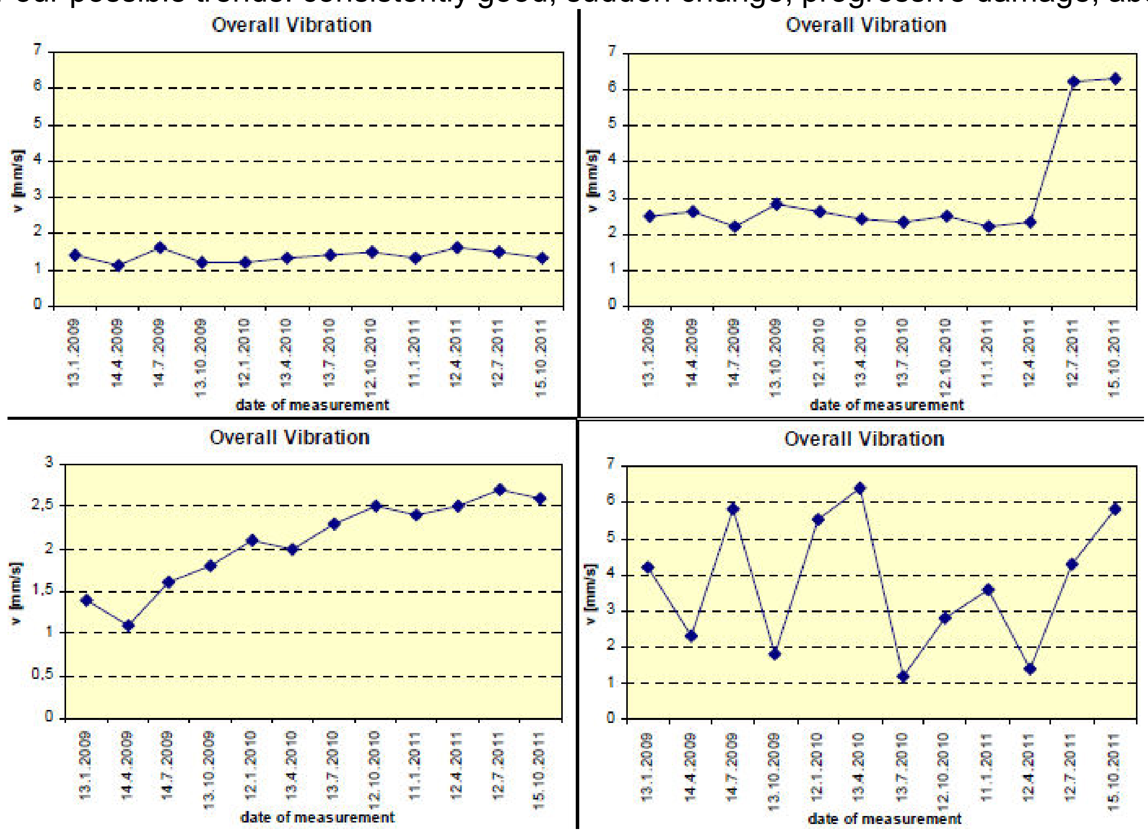
Condition Monitoring and Fault Detection of Induction Motors

- Monitoring of overall vibration level
  - Vibration magnitude monitoring
    - Total RMS value of vibration velocity in frequency range from 10 to 1000 Hz
    - Four quality zones – A, B, C and D



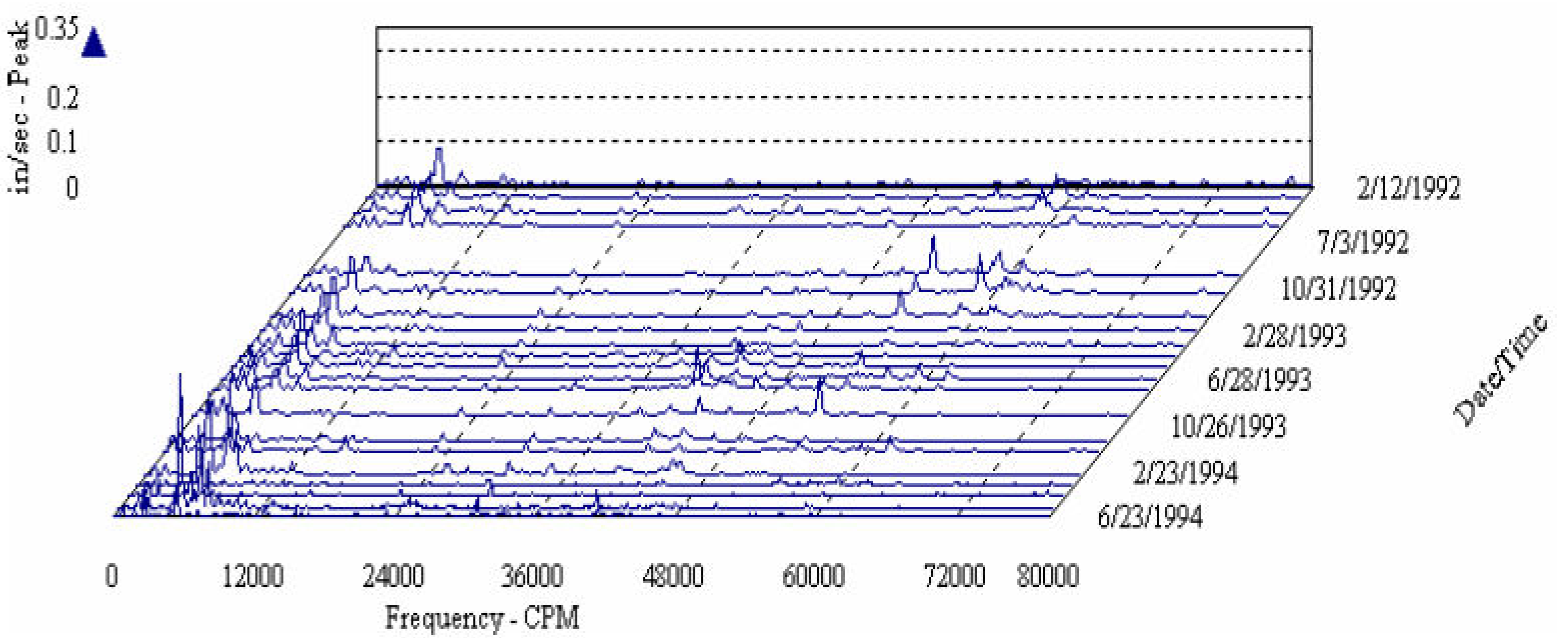
Condition Monitoring and Fault Detection of Induction Motors

- Monitoring of overall vibration level
  - Change in vibration magnitude monitoring
    - Vibration magnitude is measured and monitored over time
    - Four possible trends: consistently good, sudden change, progressive damage, absurd trend



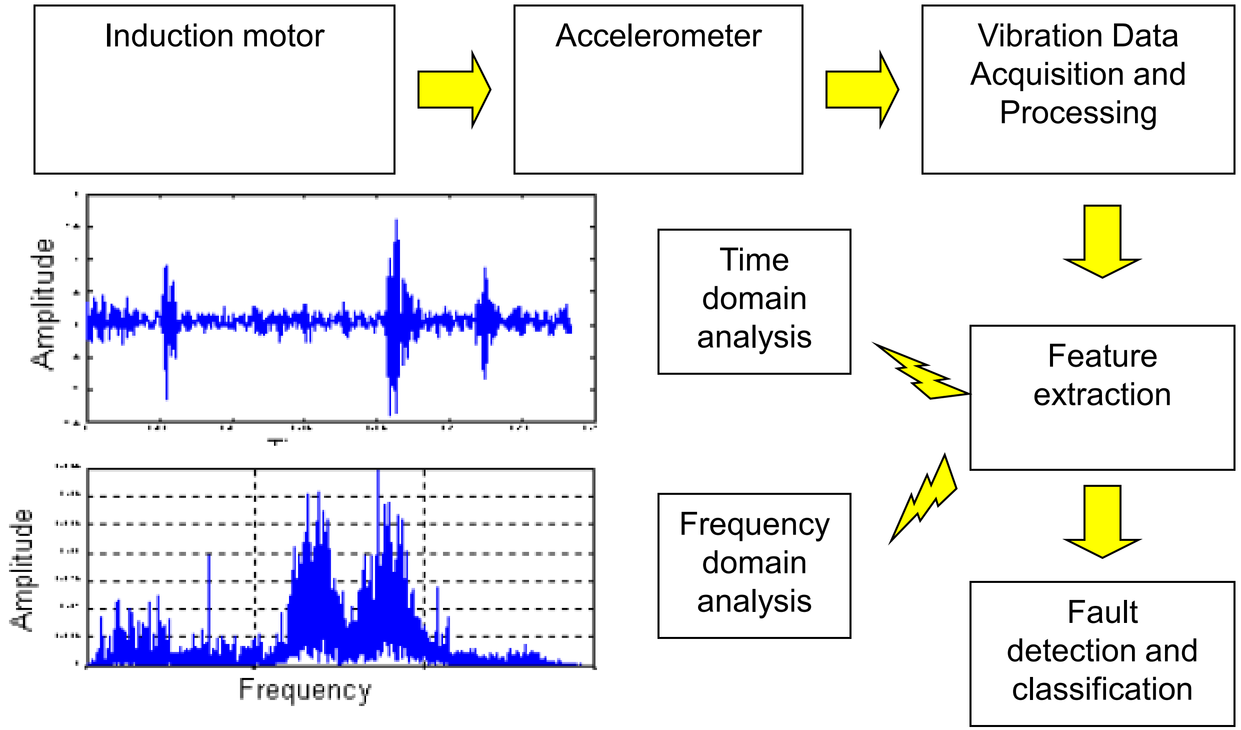
Condition Monitoring and Fault Detection of Induction Motors

- Monitoring of overall vibration level
  - Change in vibration magnitude monitoring
    - Vibration magnitude is measured and monitored over time
    - Waterfall diagrams



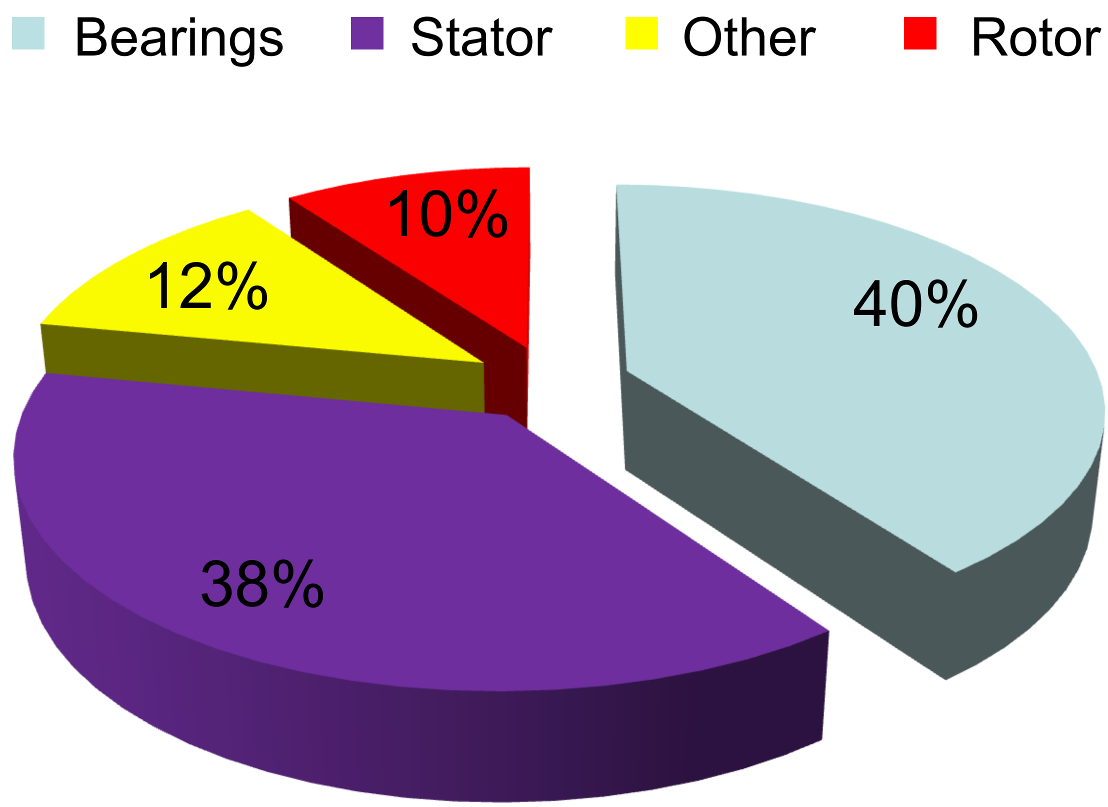
Vibration analysis in induction motor fault detection

- System for fault detection:
  - Vibration data acquisition
  - Time and frequency domain features calculation
  - Feature extraction
  - Fault detection and classification



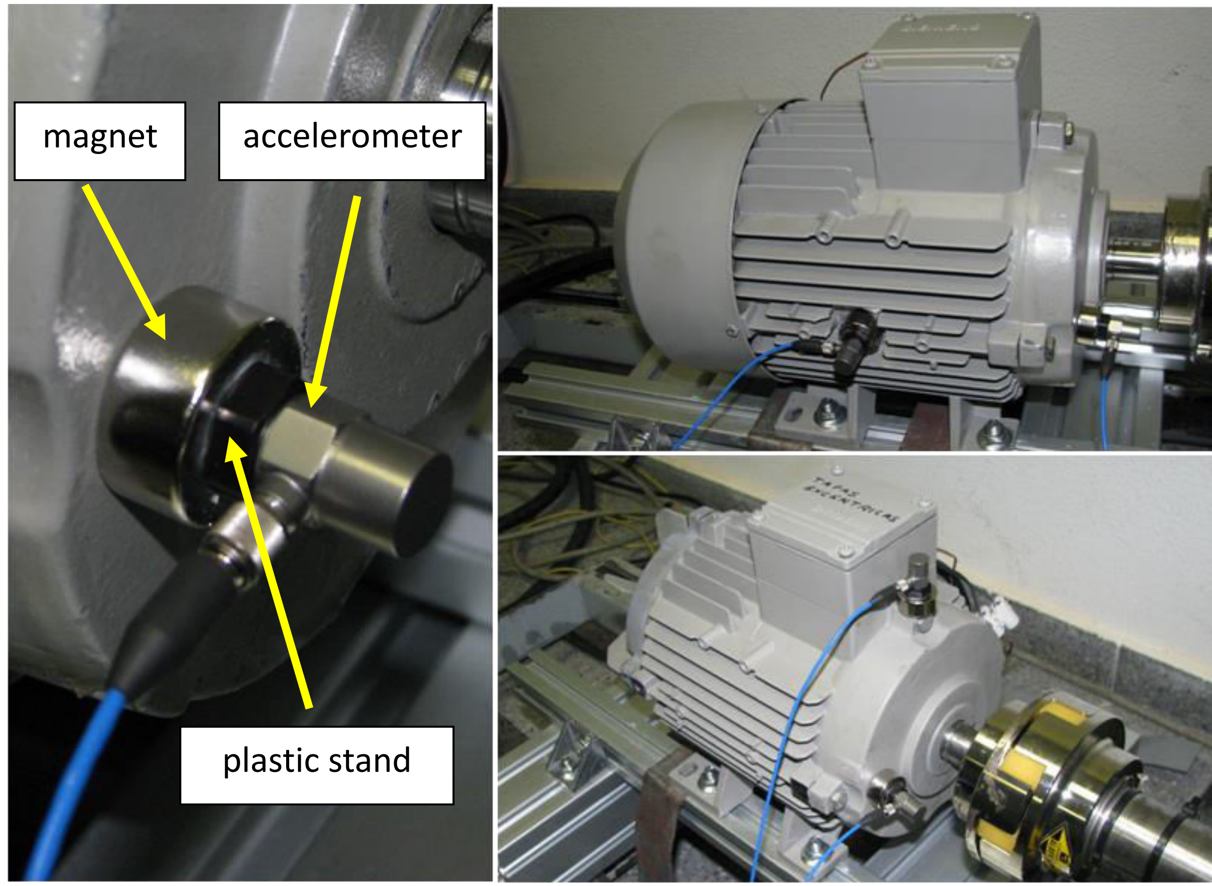
Vibration analysis in induction motor fault detection

- Typical faults of induction motors



Data acquisition equipment

- High-sensitivity IEPE (Integral Electronic Piezoelectric) accelerometers (100 mV/g) with magnetic casing for collecting signals of horizontal/vertical or radial/axial vibrations.



Data acquisition equipment

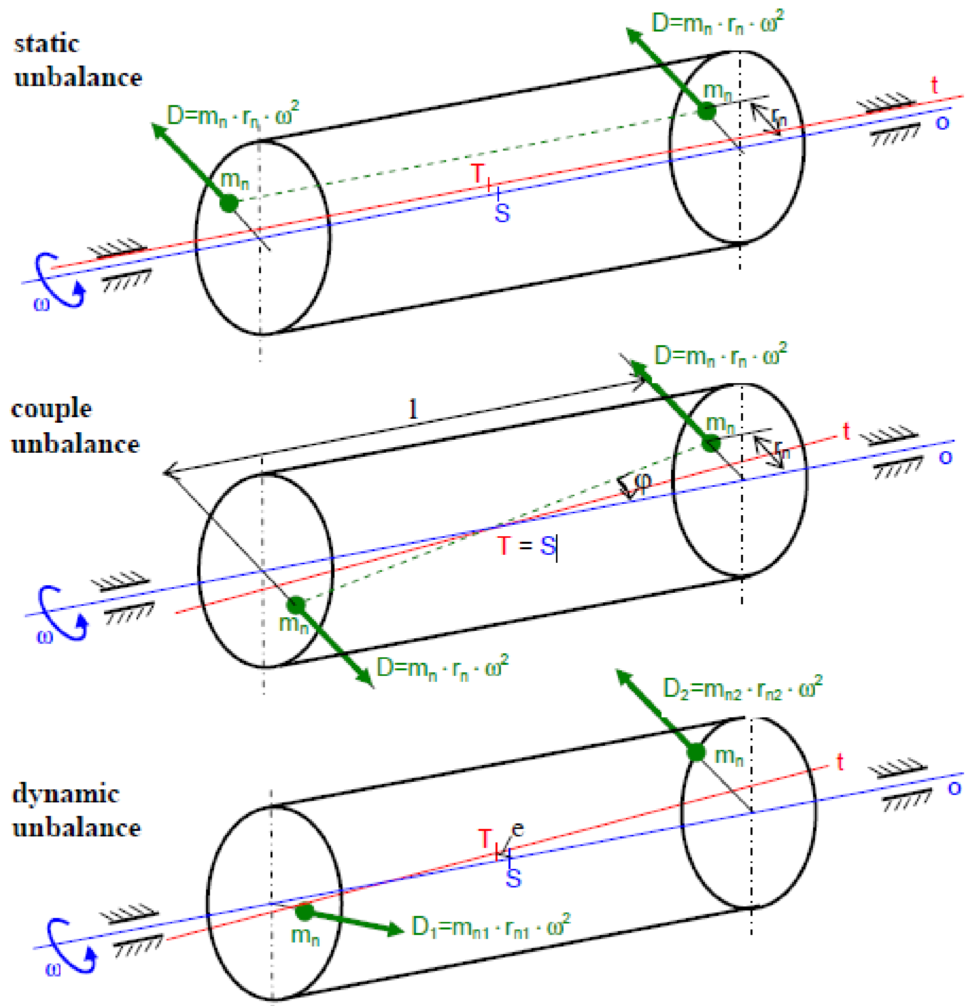
- High-sensitivity IEPE (Integral Electronic Piezoelectric) accelerometers (100 mV/g) with magnetic casing for collecting signals of horizontal/vertical or radial/axial vibrations.
- Data acquisition card NI-9234 (4 channel, ±5V, 52,2 kS/s, with 2mA IEPE accelerometer excitation)
- LabView software package for signal collection and processing.

Time domain analisys

- Time domain features:
  - Arithmetic mean value
  - Root mean square value
  - Square mean root value
  - Skewness index
  - Kurtosis index
  - *C* factor
  - *L* factor
  - *S* factor
  - *I* factor
  - ...

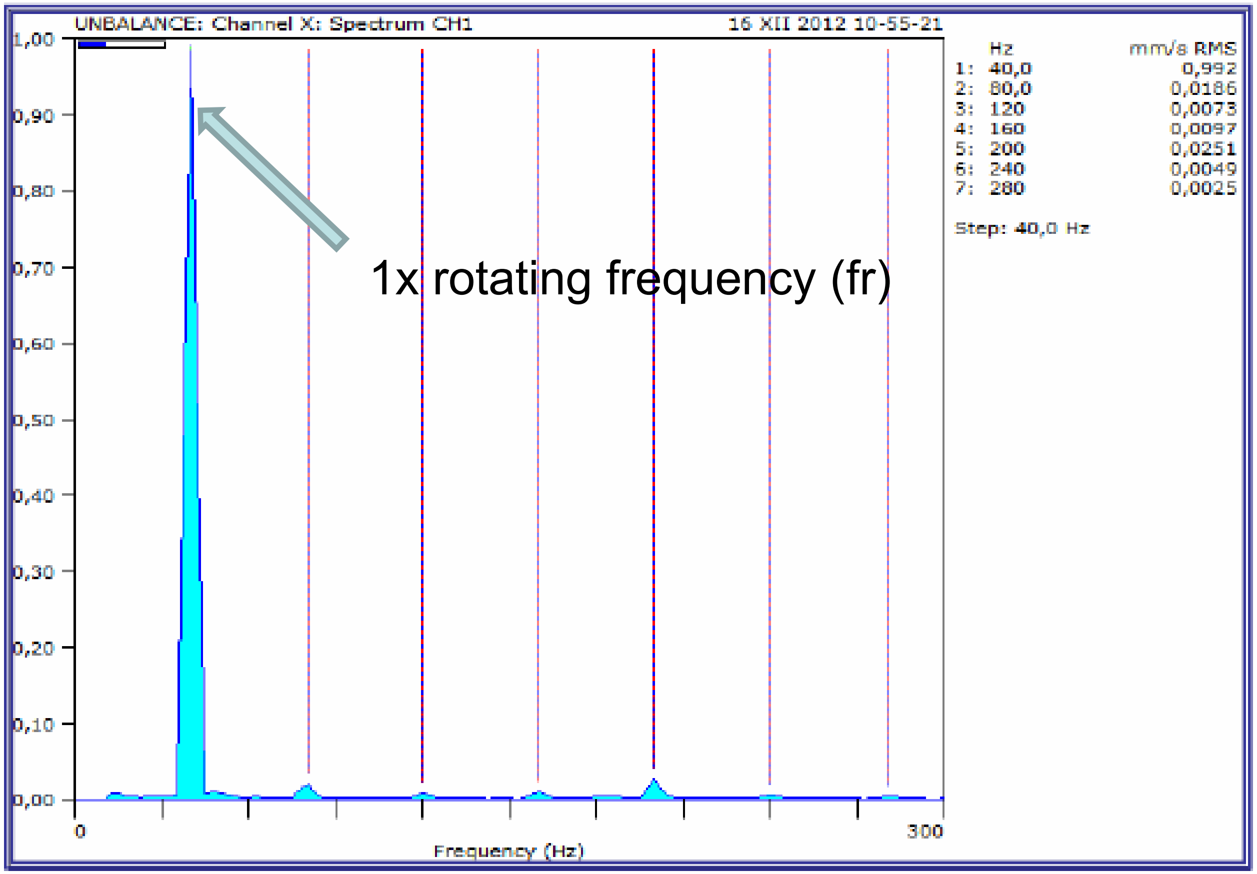
Frequency domain features (Characteristic frequencies overview)

- Mass unbalance



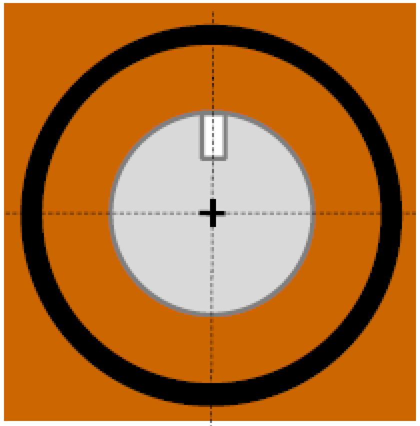
Frequency domain features (Characteristic frequencies overview)

- Mass unbalance
  - Characteristic vibration spectrum

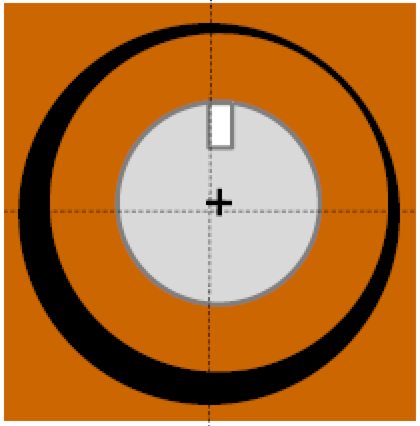


Frequency domain features (Characteristic frequencies overview)

- Static airgap eccentricity
  - Position of minimum radial gap is fixed
  - Root causes
    - Stator core ovality
    - Manufacturing tolerances in stator core or bearing
    - Incorrect installation of stator core or bearing at commissioning
  - Degree of SE usually does not change over time due to stiffness of steel



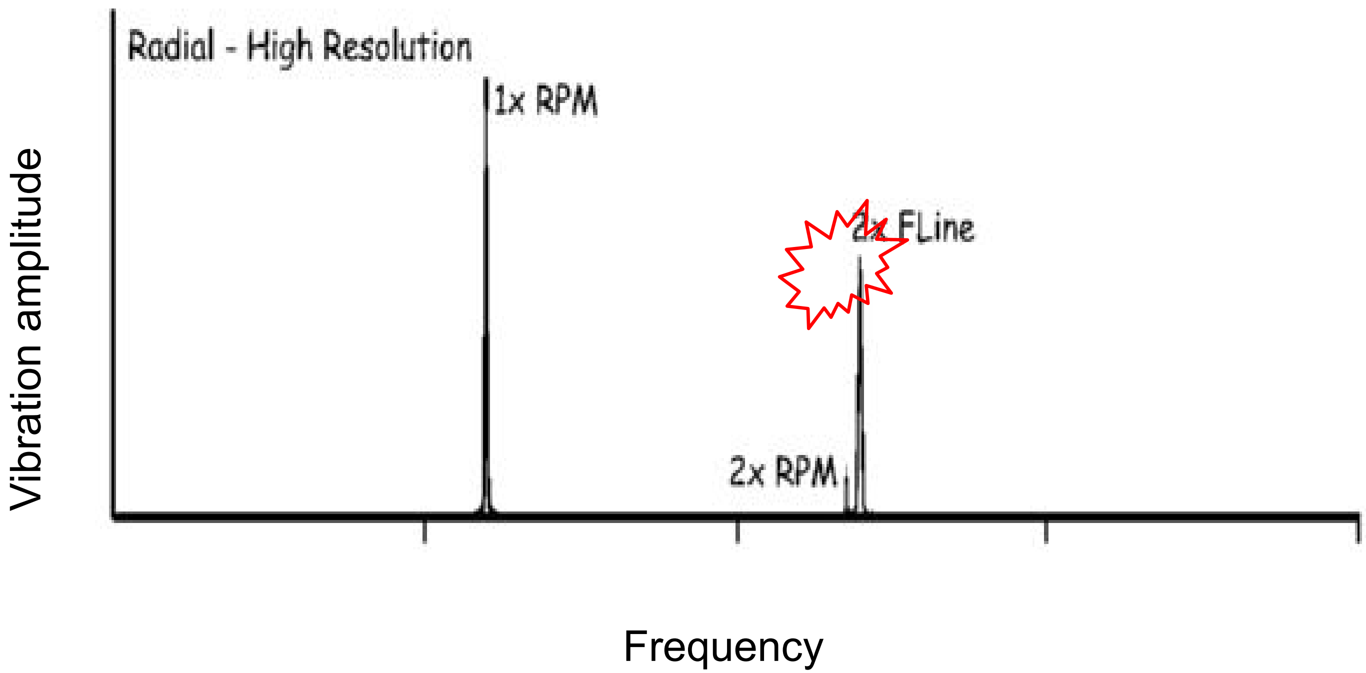
Concentric



Static eccentricity

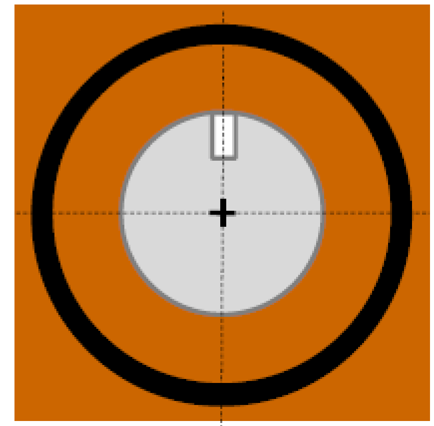
Frequency domain features (Characteristic frequencies overview)

- Static eccentricity
  - 2x supply frequency

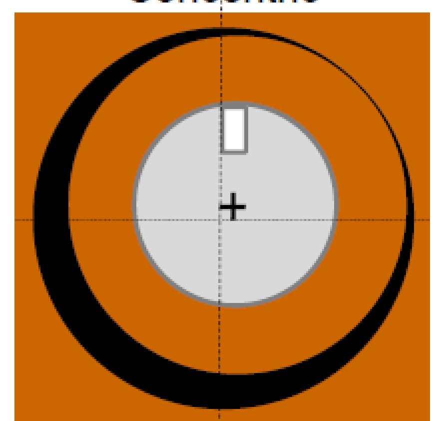


Frequency domain features (Characteristic frequencies overview)

- Dynamic airgap eccentricity
  - Position of minimum radial gap rotates with the rotor
  - Root causes
    - Bearing wear
    - Bent shaft, flexible rotor, asymetric thermal expansion
  - Degree of DE can increase over time



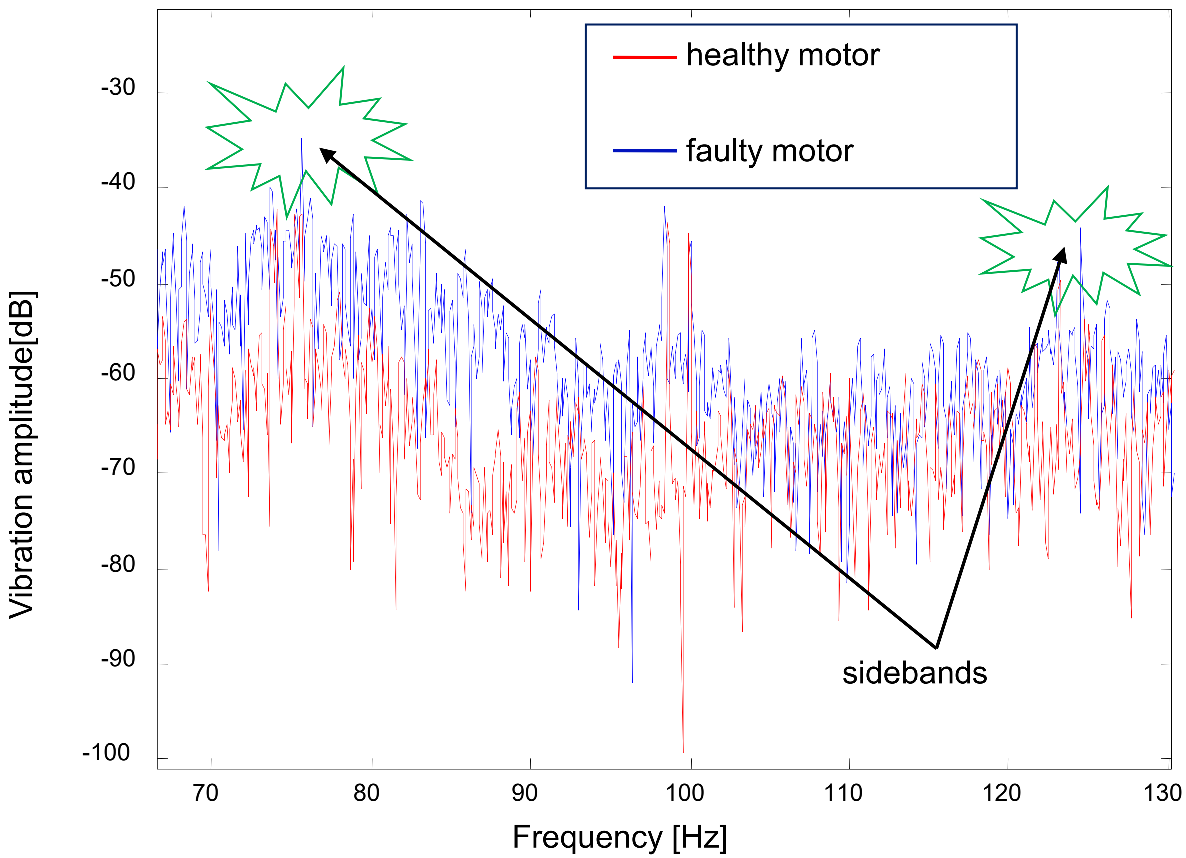
Concentric



Dynamic eccentricity

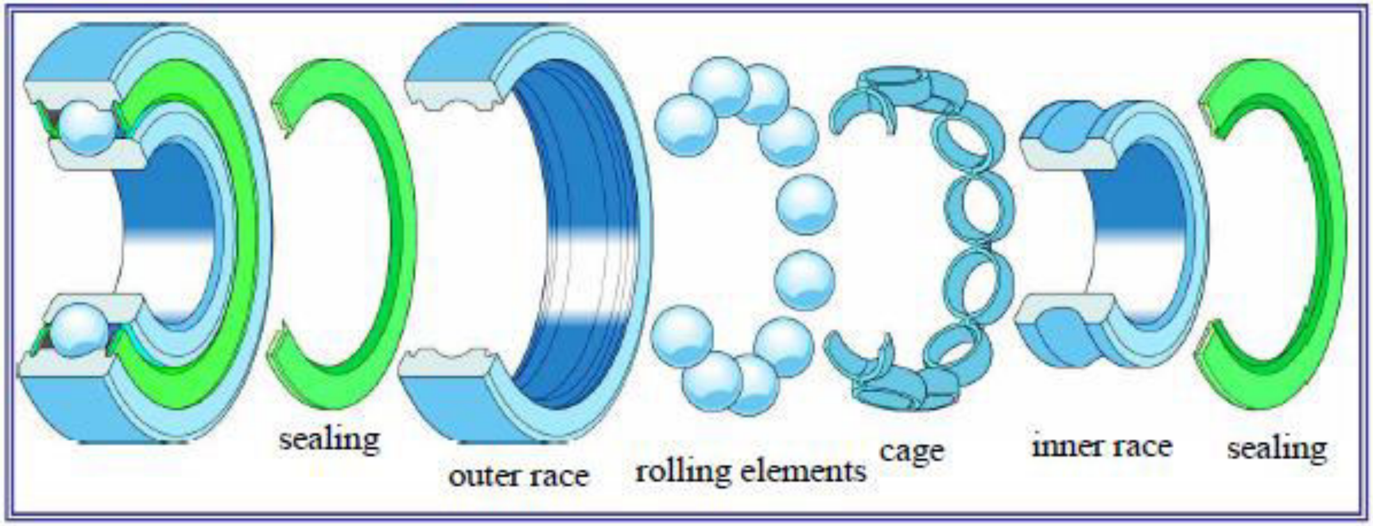
Frequency domain features (Characteristic frequencies overview)

- Dynamic airgap eccentricity
  - Sidebands : $f = 2f_s \pm f_r$



Frequency domain features (Characteristic frequencies overview)

- Bearing wear
  - Rolling element bearing construction



Frequency domain features (Characteristic frequencies overview)

- Bearing wear
  - **fault of outer race**
  - fault of inner race
  - fault of rolling element
  - fault of the cage

a slight scrape on the outer race

Frequency domain features (Characteristic frequencies overview)

- Bearing wear
  - fault of outer race
  - **fault of inner race**
  - fault of rolling element
  - fault of the cage

Frequency domain features (Characteristic frequencies overview)

- Bearing wear
  - fault of outer race
  - fault of inner race
  - **fault of rolling element**
  - fault of the cage

Frequency domain features (Characteristic frequencies overview)

- Bearing wear
  - fault of outer race
  - fault of inner race
  - fault of rolling element
  - **fault of the cage**

Frequency domain features (Characteristic frequencies overview)

- Bearing wear
  - fault of outer race

$$f_{rpfo} = f_r \times \frac{N}{2}\left(1 - \frac{d}{D}\cos\alpha\right)$$

  - fault of inner race

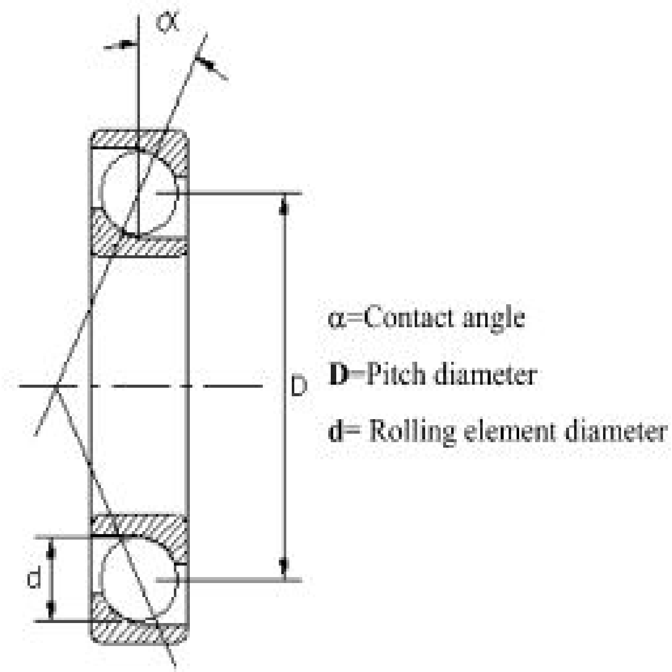
$$f_{bpfi} = f_r \times \frac{N}{2}\left(1 + \frac{d}{D}\cos\alpha\right)$$

  - fault of rolling element

$$f_{bsf} = f_r \times \frac{D}{d}\left(1 - \left(\frac{d}{D}\right)^2 \cos^2\alpha\right)$$

  - fault of the cage

$$f_{ftf} = f_r \times \frac{1}{2}\left(1 - \frac{d}{D}\cos\alpha\right)$$



Frequency domain features (Characteristic frequencies overview)

- Bearing wear
  - fault of outer race

$$f_{rpfo} = f_r \times \frac{N}{2}\left(1 - \frac{d}{D}\cos\alpha\right)$$

  - fault of inner race

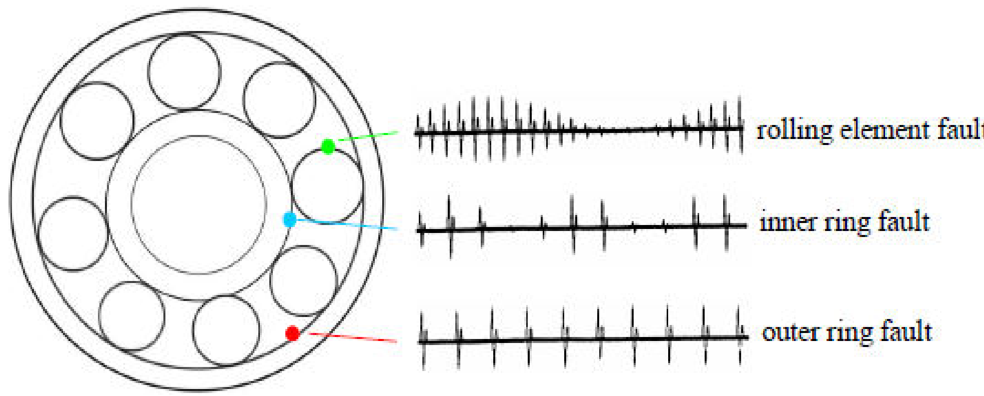
$$f_{bpfi} = f_r \times \frac{N}{2}\left(1 + \frac{d}{D}\cos\alpha\right)$$

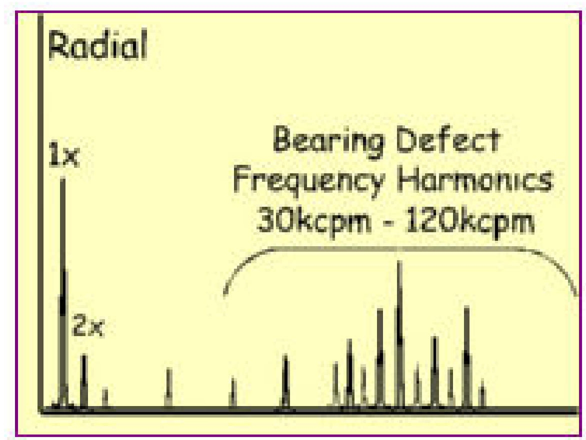
  - fault of rolling element

$$f_{bsf} = f_r \times \frac{D}{d}\left(1 - \left(\frac{d}{D}\right)^2 \cos^2\alpha\right)$$

  - fault of the cage

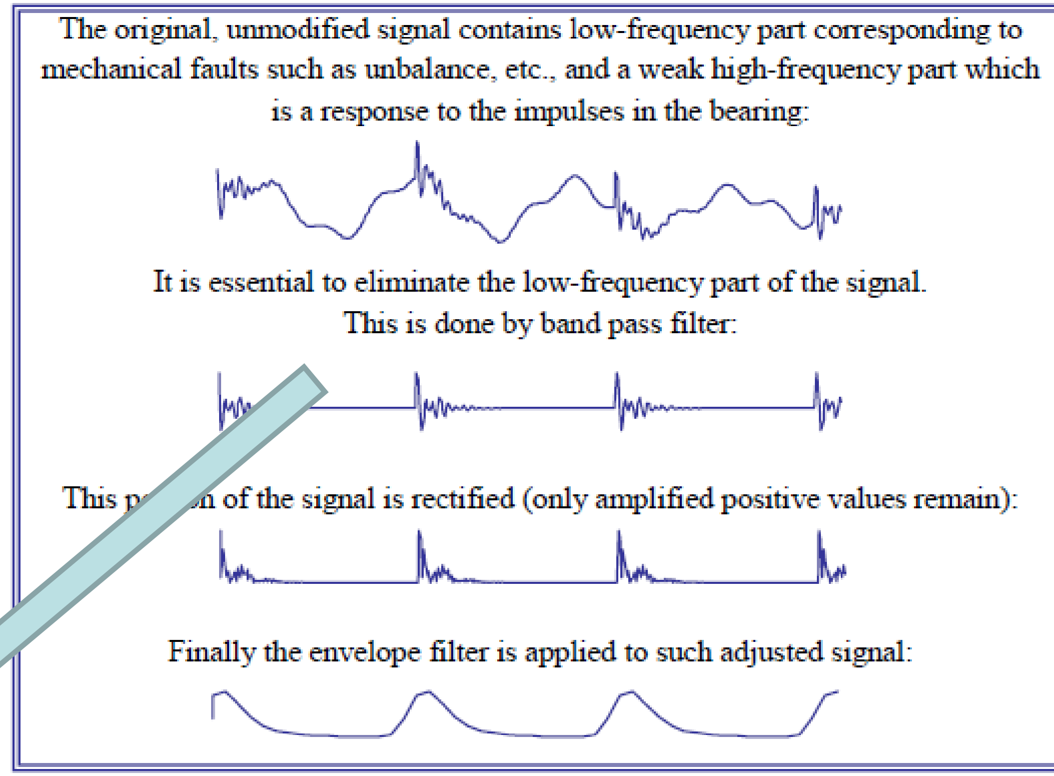
$$f_{ftf} = f_r \times \frac{1}{2}\left(1 - \frac{d}{D}\cos\alpha\right)$$





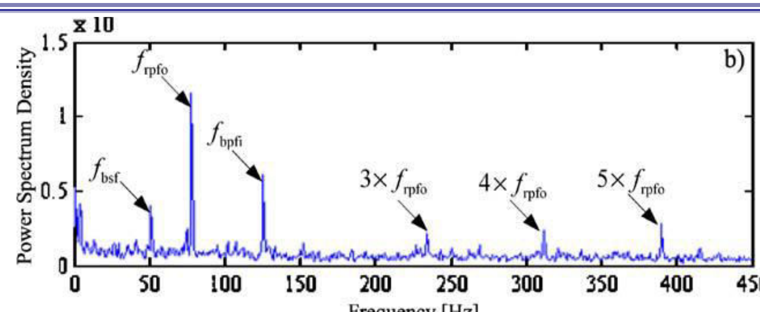
Frequency domain features (Characteristic frequencies overview)

- Bearing wear
  - Not easy to determine from unprocessed vibration spectrum
  - Characteristic frequencies covered by low-frequency noise
  - Solution – envelope analysis
  - Standardized procedure



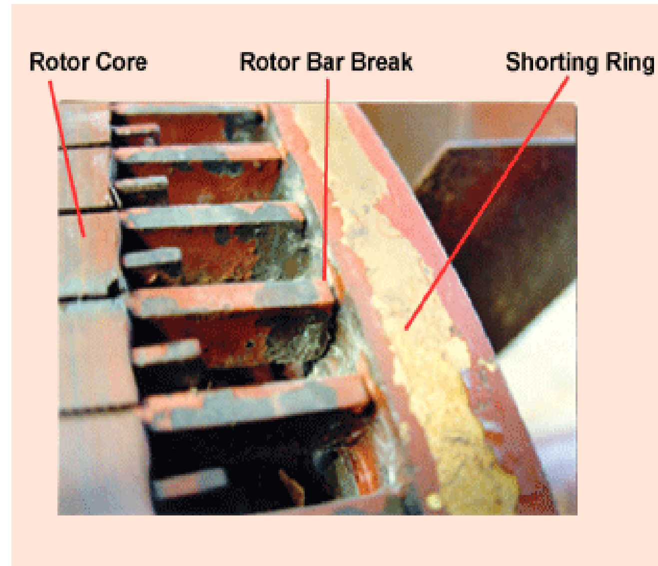
Enveloping Settings Microlog

Filters	Frequency Band	Speed Range	Analyzing Range
1	5 – 100 Hz	0 – 50 RPM	0 – 10 Hz
2	50 – 1,000 Hz	25 – 500 RPM	0 – 100 Hz
3	500 – 10,000 Hz	250 – 5,000 RPM	0 – 1,000 Hz
4	5,000 – 40,000 Hz	2,500 – ... RPM	0 – 10,000 Hz



Frequency domain features (Characteristic frequencies overview)

- Broken rotor bar
  - Frequent starts, high load variation, manufacturing defects
  - Thermal and mechanical stresses
  - Cracks typically develop at the endring and progress further in radial or axial direction
  - Increase in vibration, noise, torque decrease

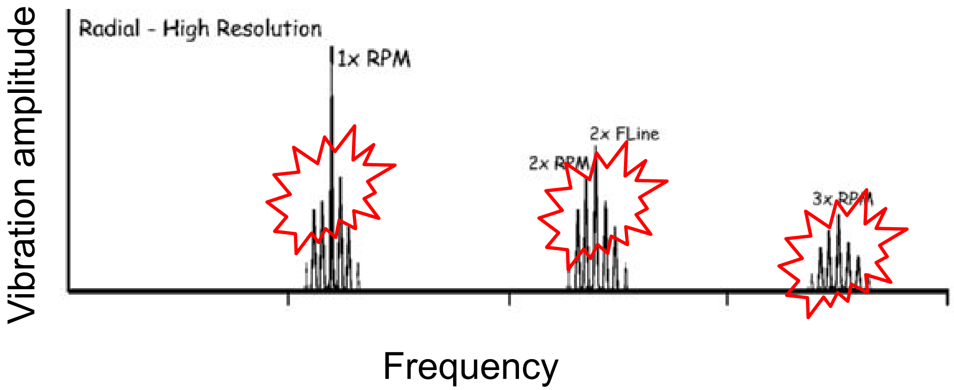


Frequency domain features (Characteristic frequencies overview)

- Broken rotor bar
  - Low frequency domain

$$f = f_r \pm k \cdot f_p, \;\; k = 1,2,3...$$

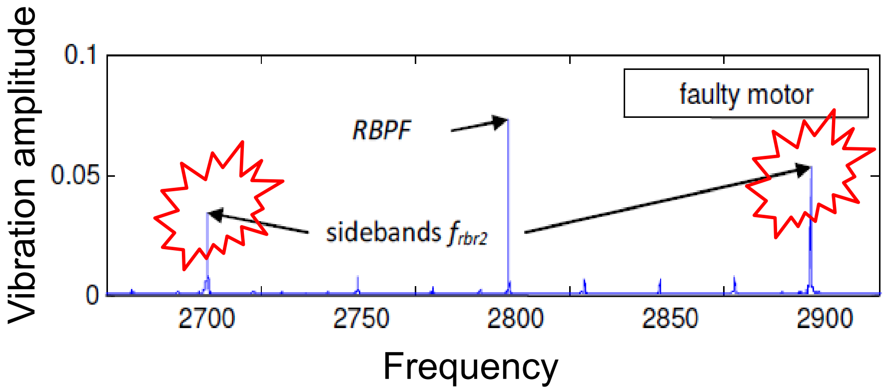
$$f_p = (f_s - f_r) \cdot p$$



  - High frequency domain

$$RBPF = f_r \cdot Nr$$

$$f_{brb2} = RBPF \pm 2f$$

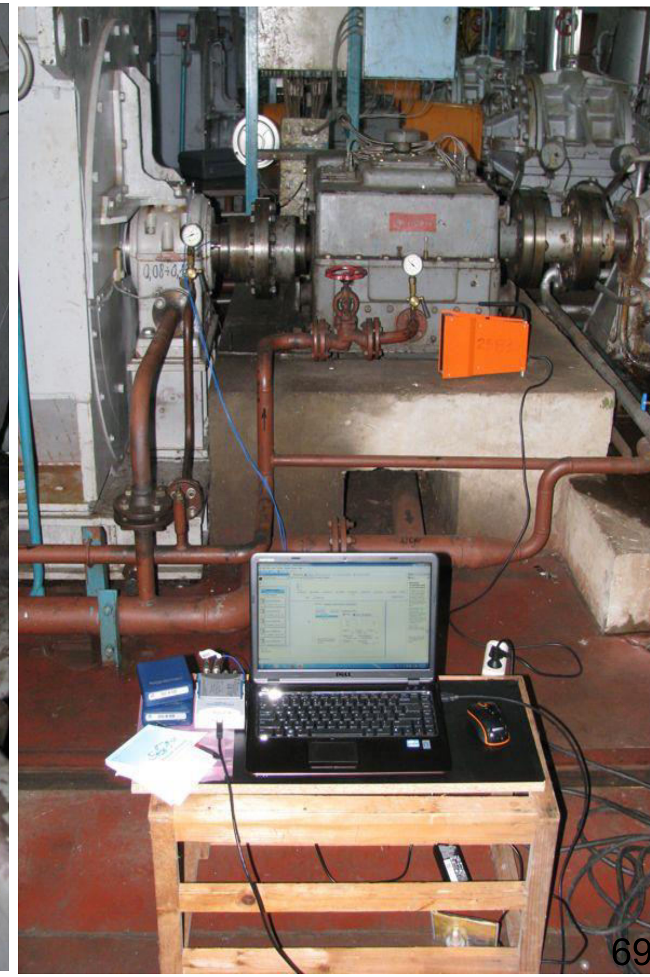


- High resolution necessary!

Application Example 1

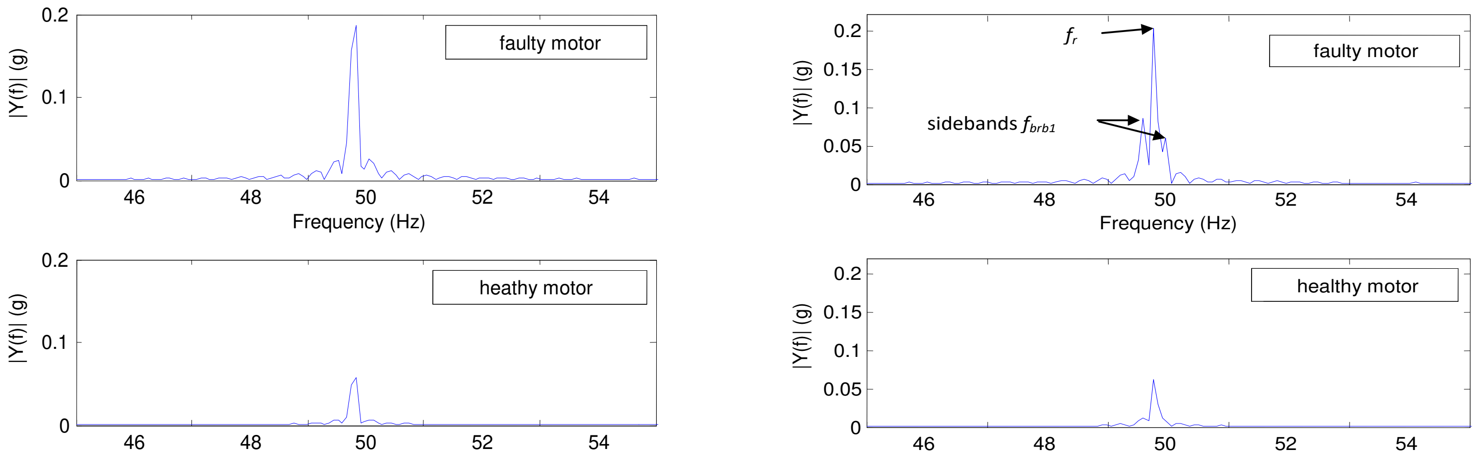
- 3,2 kW Induction Motor in Heating Power Plant
- Increased level of vibration and acoustic noise
- Decreased momentum



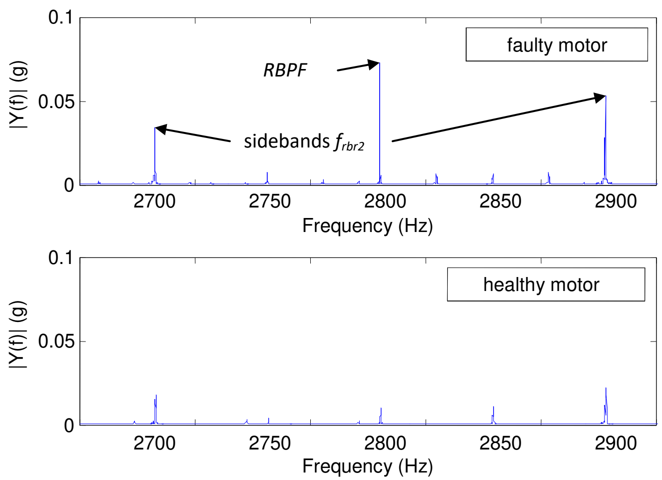



Application Example 1

- Vibration spectrum – low frequency domain
- Different load levels

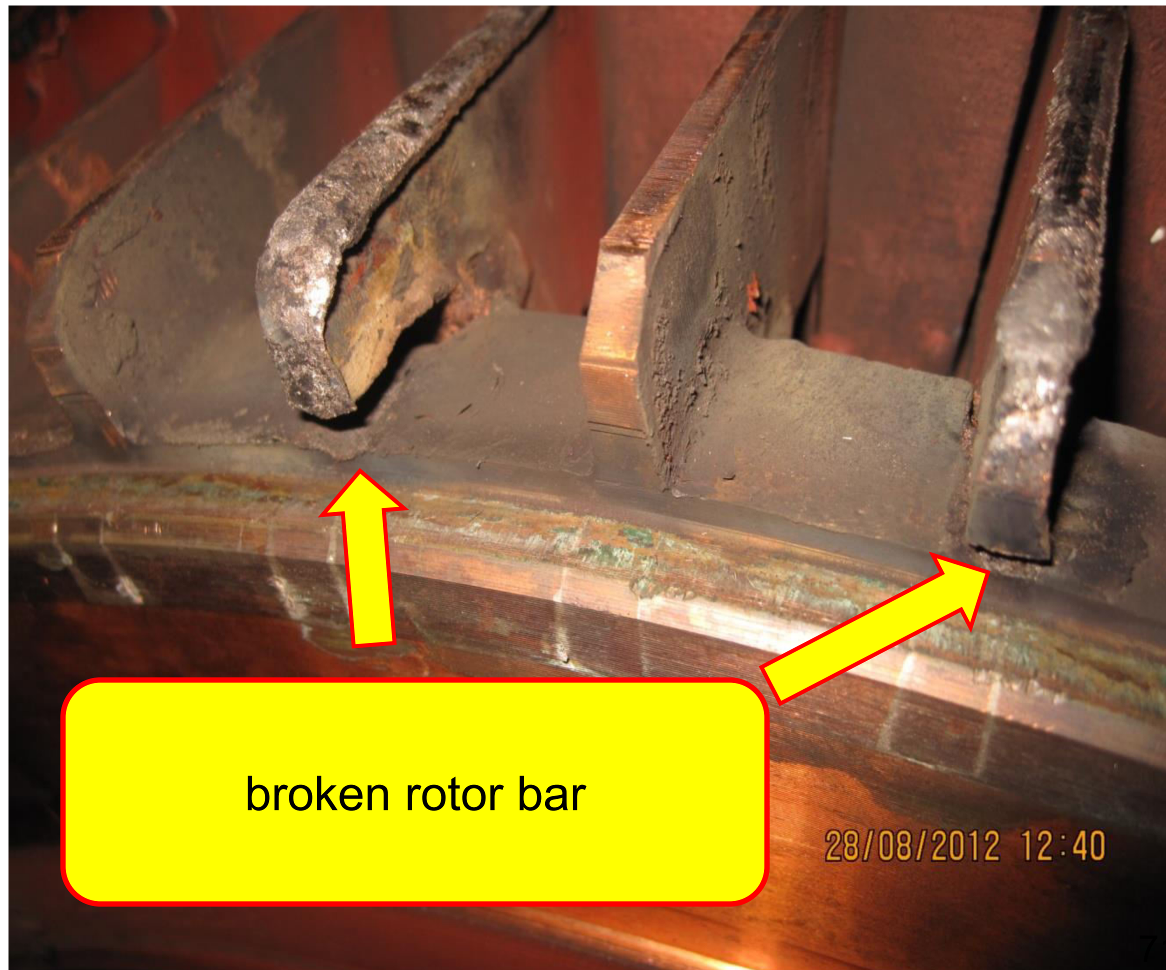


- Vibration spectrum – high frequency domain



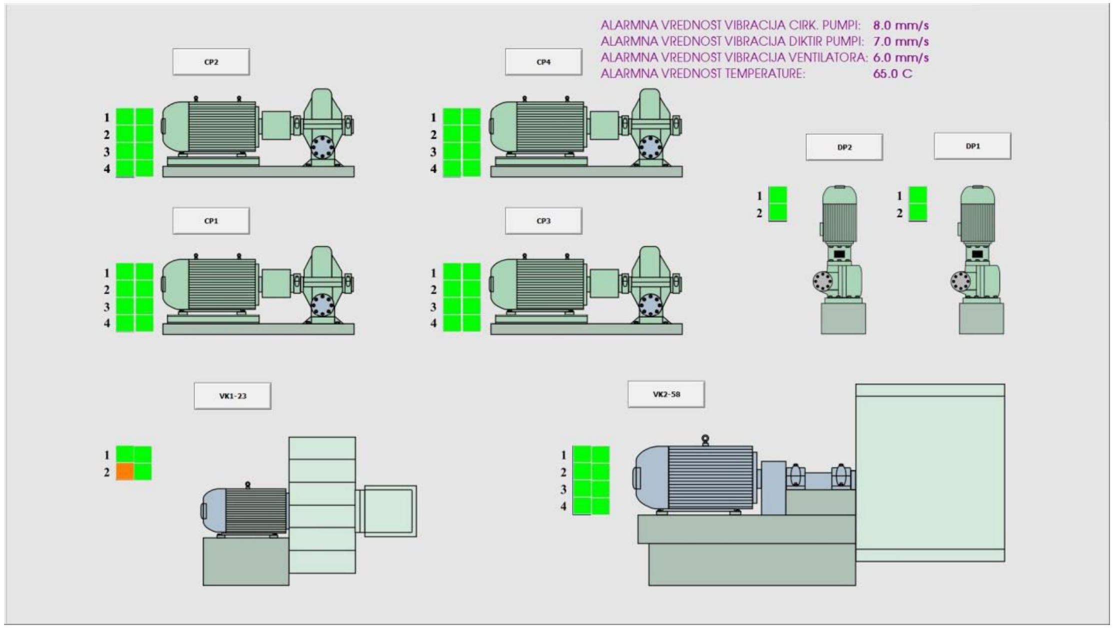
Application Example 1

- Broken rotor bar detected!



Application Example 2

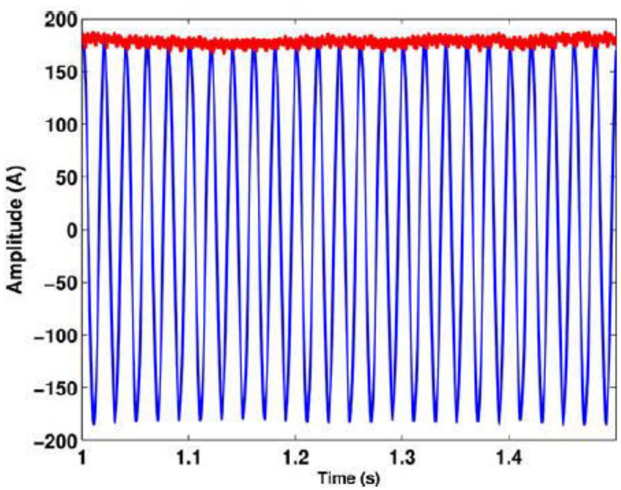
- District heating plant
- Pump motors supplied with frequency controlers, controled by pressure value
- Increased level of vibration, rapid bearing deterioration

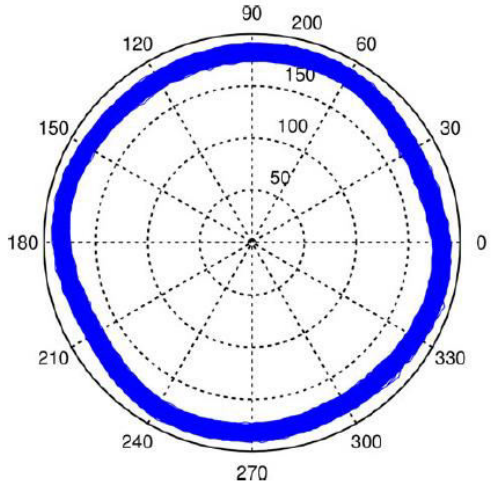


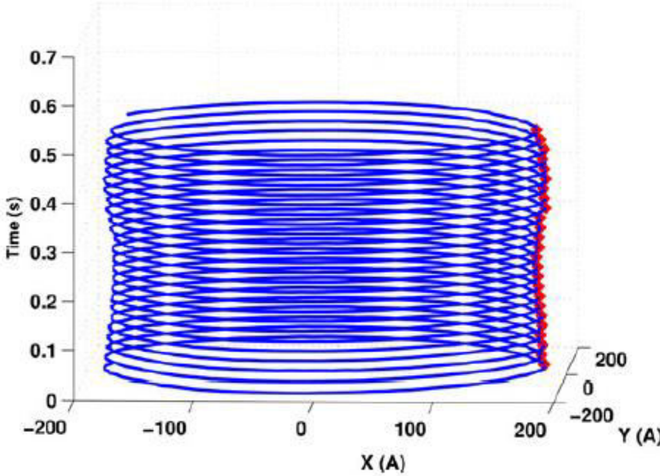
- Cause – operating point in the resonance area!

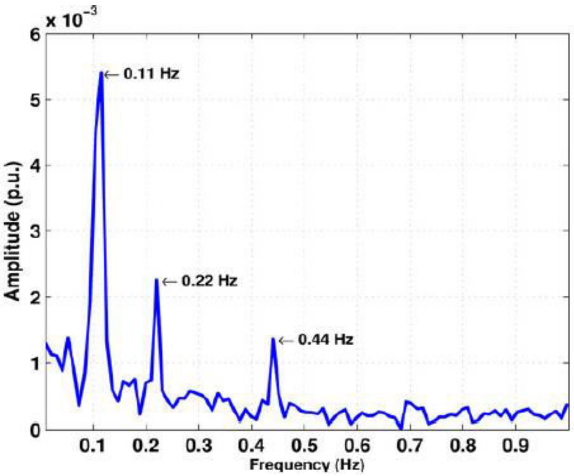
Further research

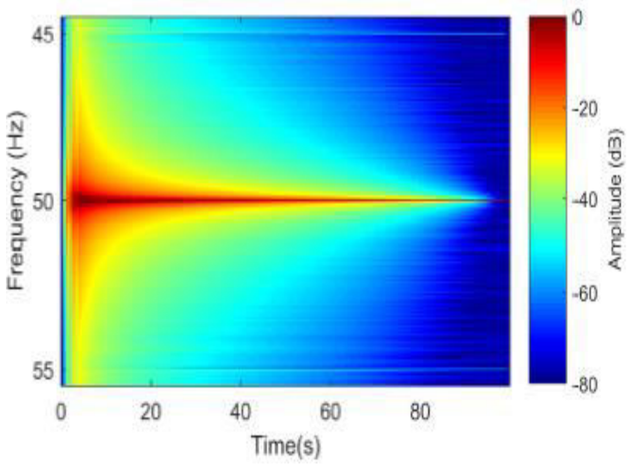
- Advanced signal processing techniques

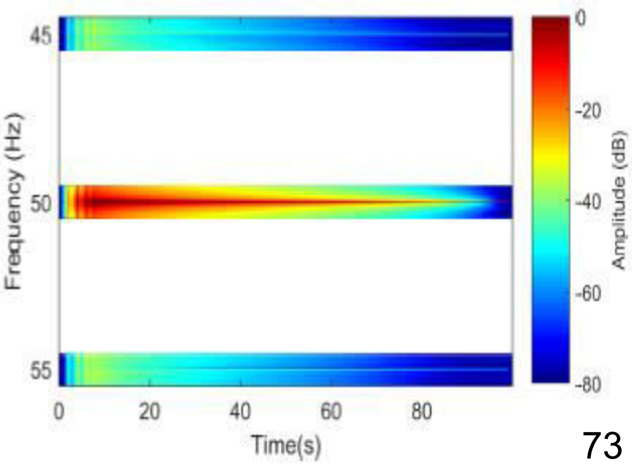






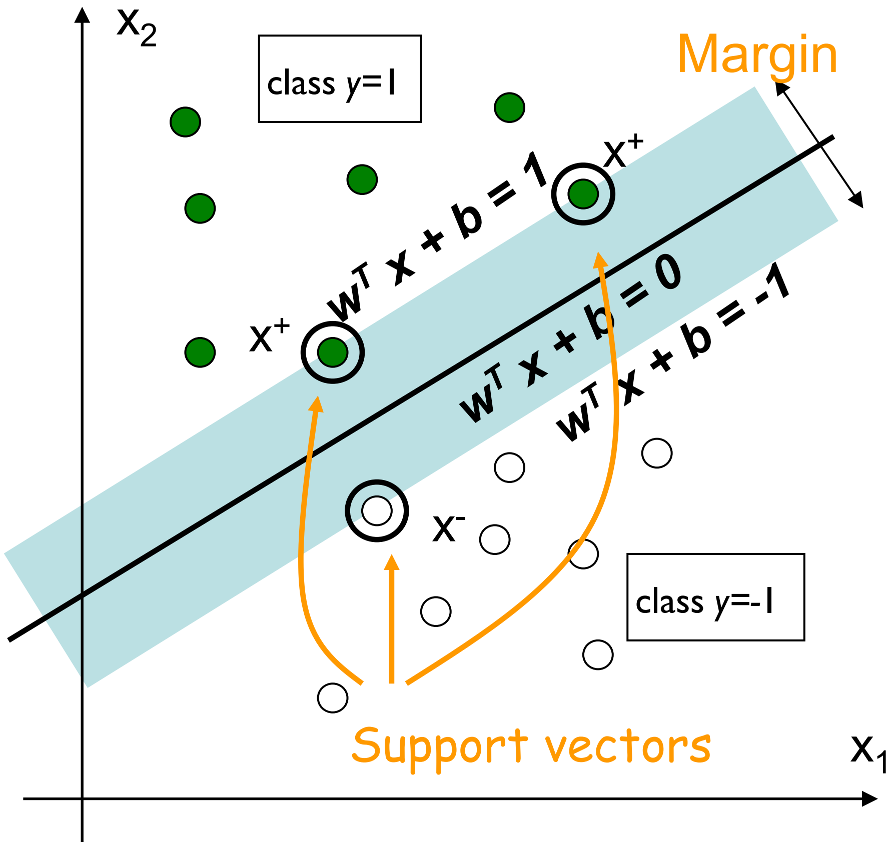


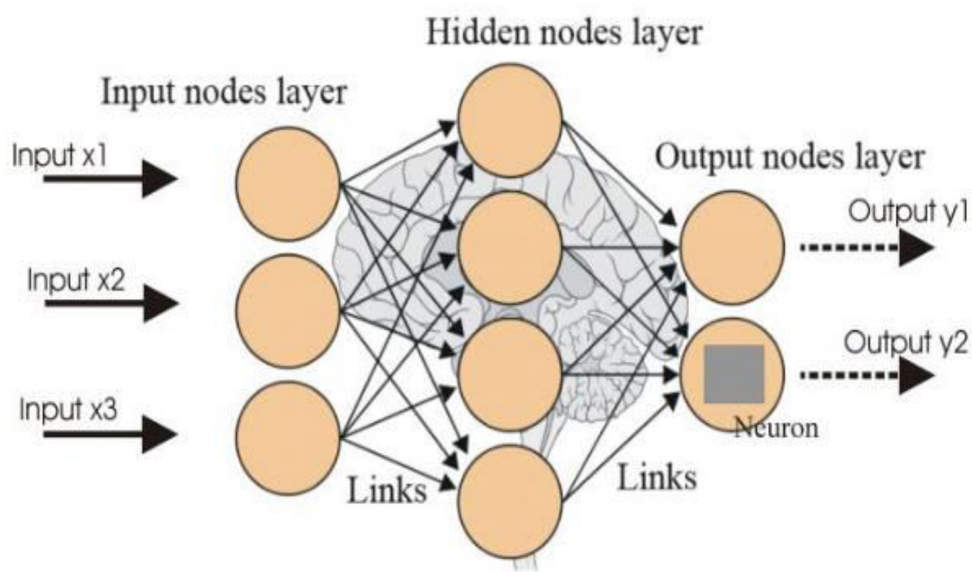




Further research

- Expert systems for fault detection and classification





74

Thank You for Your Attention!

Questions, Suggestions, Comments…?