Fault Detection in Rotating Machinery:

vibration analysis and numerical modeling

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Planetary Gearbox

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Planetary Gears are Widely Used:

- Aerospace
- Wind Turbines
- Automotive

Advantage:

- Compactness
- High Torque-to-Weight Ratios
- Multiple Gear Ratios

❖ Project Objectives

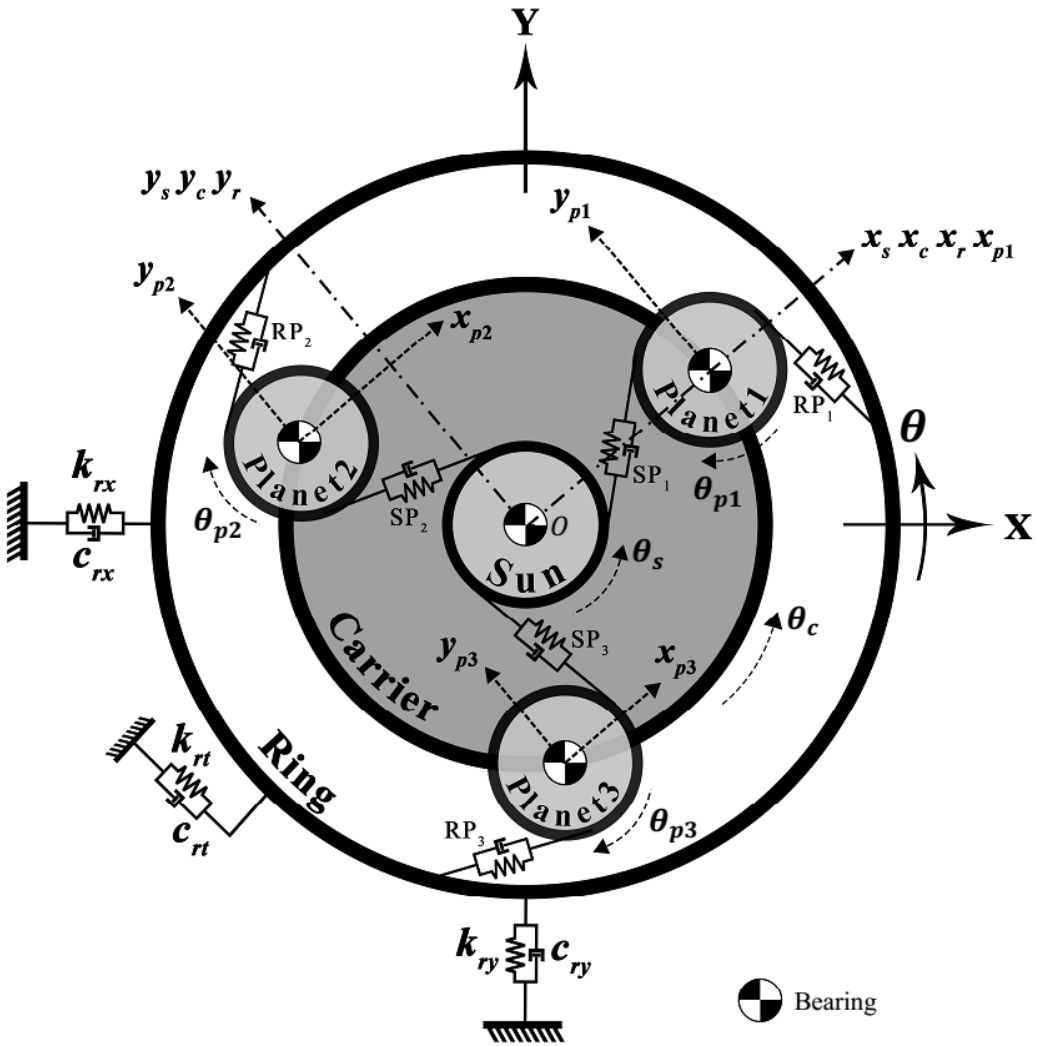
- Investigate the Vibration Properties of Planetary Gearboxes
- Diagnosis of Bearings and Gears

❖ Mathematical Model

- A Good Understanding Of Structure Dynamic Characteristics
- Reasonably Accurate
- Suitable For Evaluations During Design Stages
- Flexible

Lumped Parameter Model

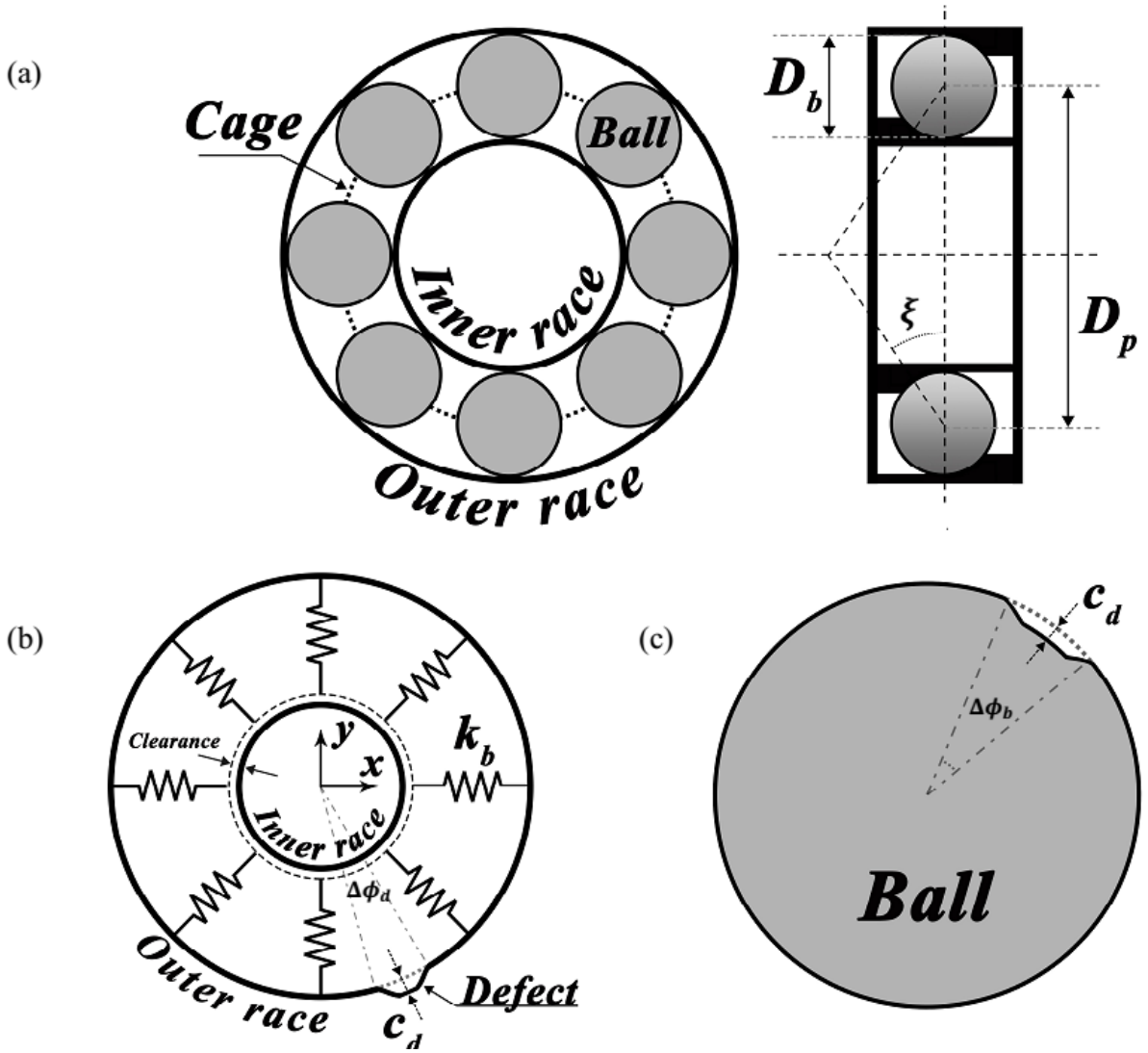
- Each Gear and the Carrier are Considered as Rigid Bodies with Three DOFs
- The Flexible Gear Teeth Contacts are Modelled by Springs and Dampers
- Comprehensive Bearing Model



❖ Time-Varying Mesh Stiffness

- Number of Teeth Pairs in Contact Change
- Contact Positions of Gear Teeth Alter
- One of the Main Sources of Vibration
- It is calculated by Potential Energy Method

Bearing Model



- Four Degrees of Freedom
- Flexibility of Rollers: Circumferentially Distributed Radial Springs
- Hertizian Contact Between Balls/Rollers and Races are Assumed

$$F_j = k_b \delta_j^n$$

n = 1.5 for ball bearings and 1.1 for roller bearings

- Overall Bearing Stiffness Varies

❖ Localized Fault Modeling

- Variation of Balls Force Inside the Defected Region
- This Variation Can Be Utilized to Detect Defects

Summarizing the model

- Capacity of Modelling Cracks and Spalls of Gears and Bearings with different sizes, locations and profiles
- Time Varying Gear Mesh and Bearing Stiffness
- Nonlinear Bearing Stiffness

Equations of Motion

- 18 Degrees of Freedom

The Sun Gear Equations of Motion

$$m_s\ddot{x}_s + F_{sbx} + \sum_{n=1}^{N} F_{spn}\cos\Psi_{sn} = m_s x_s \dot{\theta}_c^{\,2} + 2m_s\dot{y}_s\dot{\theta}_c + m_s y_s\ddot{\theta}_c,$$

$$m_s\ddot{y}_s + F_{sby} + \sum_{n=1}^{N} F_{spn}\sin\Psi_{sn} = m_s y_s \dot{\theta}_c^{\,2} - 2m_s\dot{x}_s\dot{\theta}_c - m_s x_s\ddot{\theta}_c,$$

$$\left(\frac{J_s}{r_s}\right)\ddot{\theta}_c + \sum_{n=1}^{N} F_{spn} = \frac{T_i}{r_s},$$

- Rotating Gear Frames

F_{spn} represents the gear mesh force

$$F_{spn} = k_{spn}\delta_{spn} + c_{spn}\dot{\delta}_{spn},$$

$$\delta_{spn} = \left(x_s - x_{pn}\right)\cos\Psi_{sn} + \left(y_s - y_{pn}\right)\sin\Psi_{sn} + r_s\theta_s + r_p\theta_{pn} - r_c\theta_c\cos a\ ,$$

F_{sbx} and F_{sby} represent the sun bearing force in x_s and y_s directions

$$F_{sbx} = c_{sx}\dot{x}_s + k_b\sum_{j=1}^{N_b}\gamma_j\left[x_s\cos\phi_{sj} + y_s\sin\phi_{sj} - \beta_j C_d - c\right]^{1.5}\cos\phi_{sj}$$

$$F_{sby} = c_{sy}\dot{y}_s + k_b\sum_{j=1}^{N_b}\gamma_j\left[x_s\cos\phi_{sj} + y_s\sin\phi_{sj} - \beta_j C_d - c\right]^{1.5}\sin\phi_{sj}$$

$$\phi_{sj} = \frac{2\pi(j-1)}{N_b} + \frac{\theta_s}{2}\left(1 - \frac{D_b}{D_p}\cos\xi\right) + \phi_0 - \theta_c$$

Results and Discussion

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These Coupled Nonlinear and Time Variant ODE Are Numerically Solved to Calculate the Ring Gear Acceleration Signal

❖ Planet-Bearing

- Exhibit a High Failure Rate
- Transmit the Torque From Input of the System to the Output

❖ Frequency Analysis of Defect Signals

- Faulty Inner Race, Outer Race and Rolling Element
- Residual Signals: Difference Between the Time Responses of Damaged and Undamaged Systems

Frequency Analysis of Defect Signals

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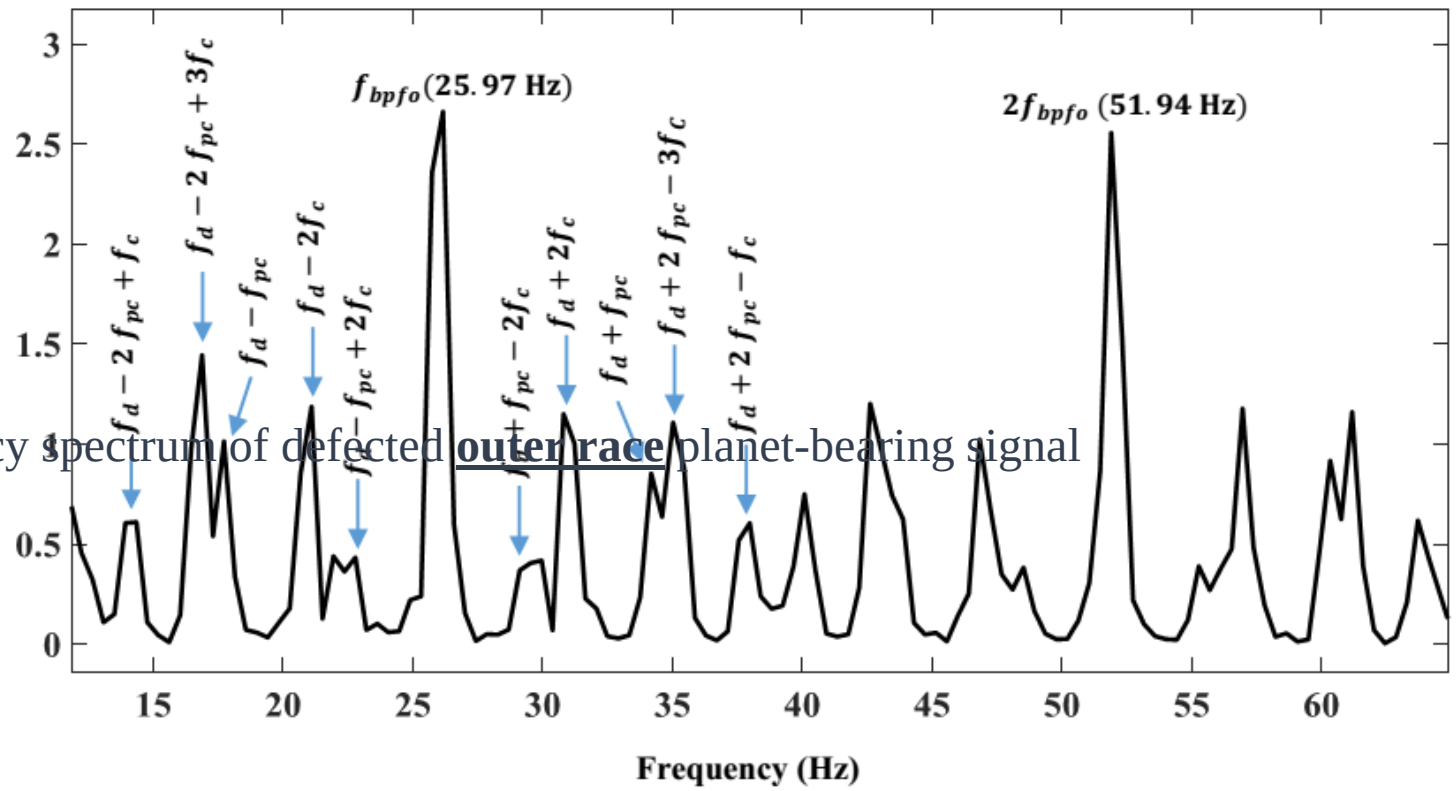
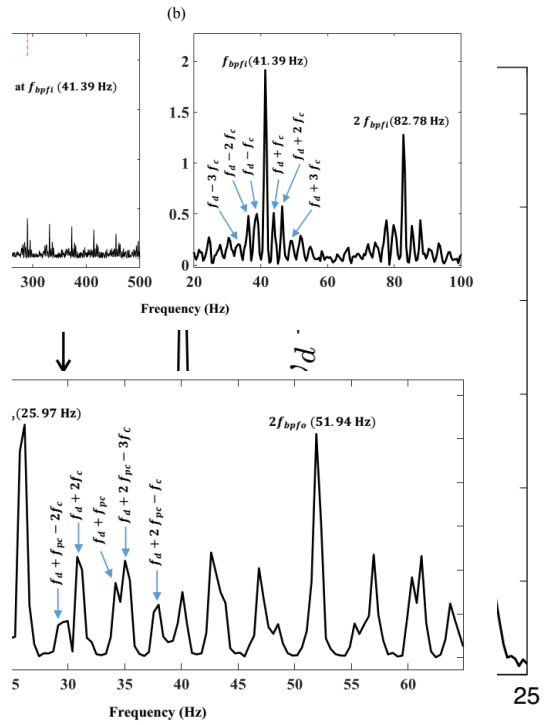
❖ Frequency spectrum of defected **inner race** planet-bearing signal



❖ Frequency spectrum of defected **outer race** planet-bearing signal



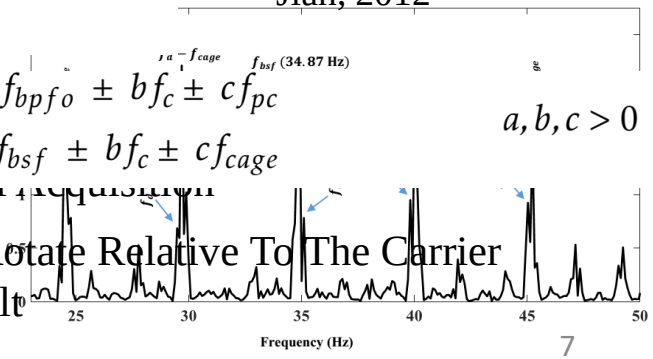
Jian, 2012

Cluster Of Sidebands:

$$f_{sidebands,o} = af_{bpfo} \pm bf_c \pm cf_{pc}$$

$$f_{sidebands,b} = af_{bsf} \pm bf_c \pm cf_{cage}$$

$$a, b, c > 0$$



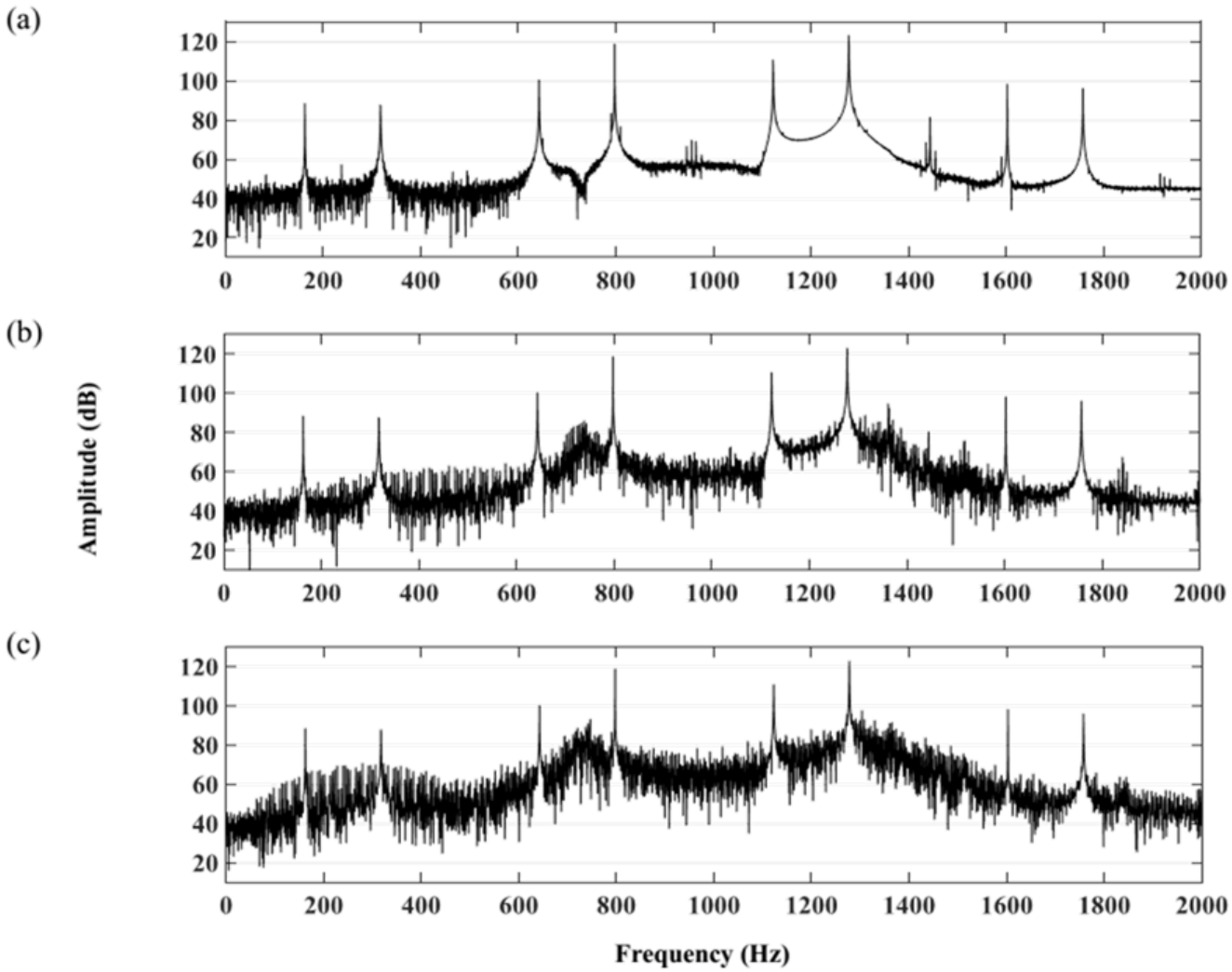
Cluster Of Sidebands:

- Carrier Rotation (f_c)
- Relative Rotation Between The Defect And The Carrier (f_{pc})
  - Carrier Rotation: The Transmission Path Between The Planet-bearing And The Signal Acquisition Point On The Ring Gear Vary With Time
  - Force Which Is Caused By The Defective Planet-bearing Outer Race Or Ball Will Rotate Relative To The Carrier
  - Ball/Roller May Lose Its Contact With The Races While It Passes Through The Fault
  - Angle Between The Defect Force And Ring-planet Mesh Varies

❖ Frequency spectrum of defected **ball** planet-bearing signal

Frequency Spectrum of the Ring Acceleration Signals

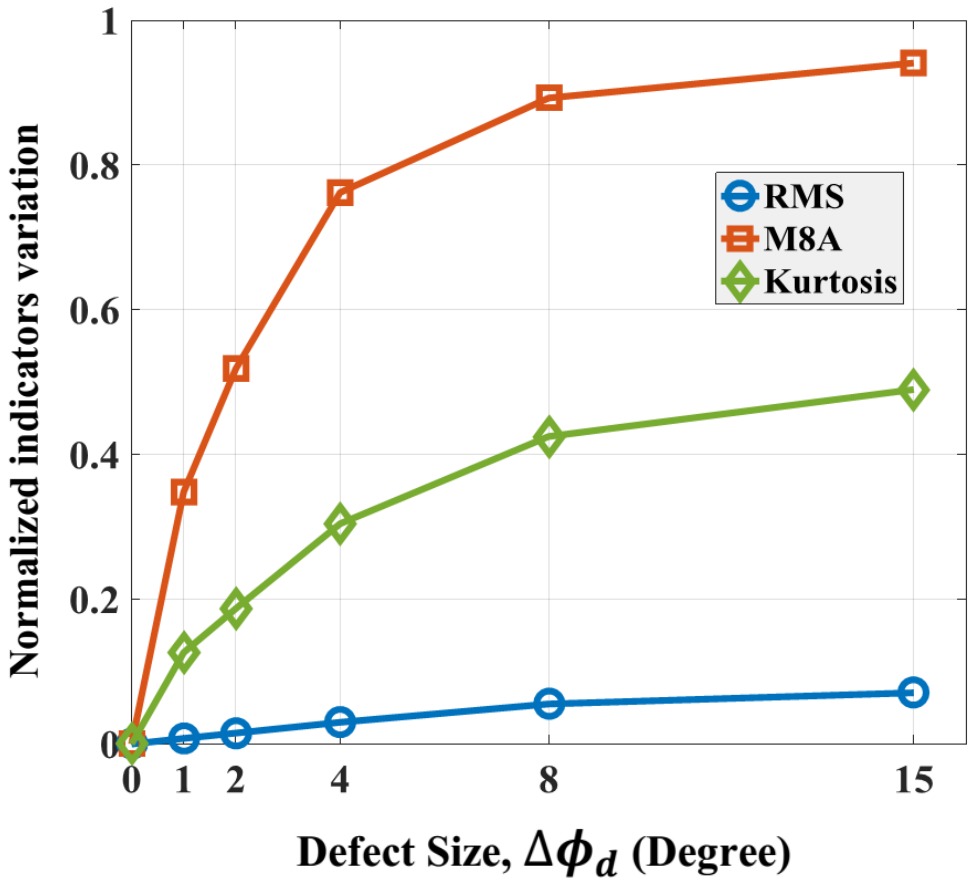
- Healthy and Defected Planet Bearing
- Sidebands Emerge When Defect Is Present
  - Combination Of BPF and Its Sidebands
- Amplitudes of Meshing Frequency and Its Harmonics are Not Affected by Faults
- Amplitudes of Sidebands Increase as the Size of Spall Grows
- These Variations are Believed to be Worthwhile for Fault Diagnosis of Planetary Gearboxes



(a) healthy gearbox (b) defected planet inner race, $\Delta\varphi_d = 2^0$ and (c) 4^0

Condition Monitoring of the Gearbox

- Statistical Features are Usually Used as an Indicator of Bearings and Gears Faults Presence and Growth
  - RMS
  - Kurtosis
  - M8A
- Condition Indicators for 5 Defect Cases
- All The Statistical Indicators Quantities Rise with the Growth of the Planet's Defect Size
- M8A Indicator is More Sensitive to the Presence of the Defects
  - Potential to Diagnose Spalls Even in Their Emerging Stages



Rolling Element Bearings

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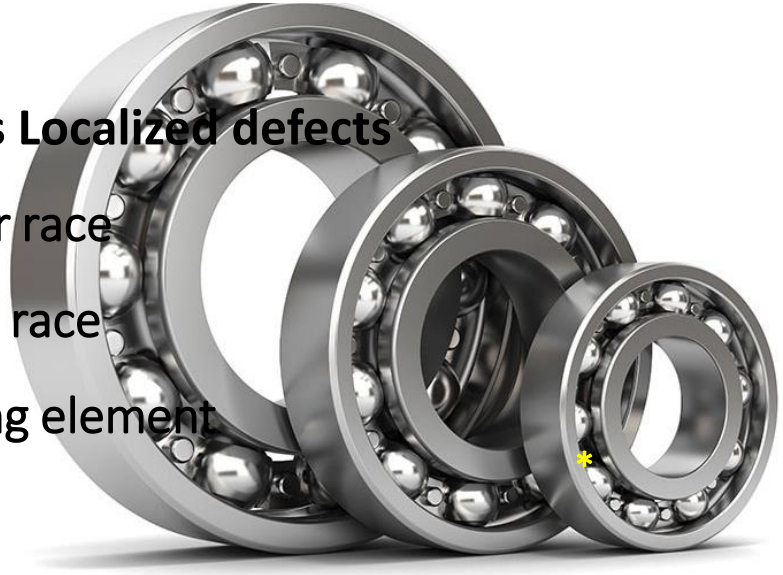
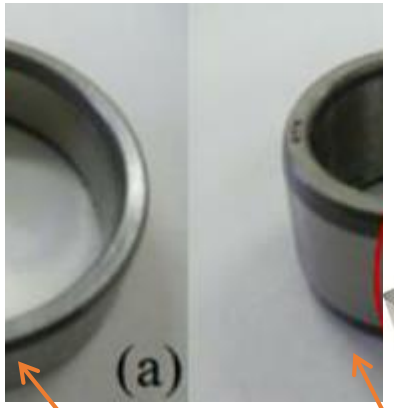


Bearings Localized defects

(a) Outer race

(b) Inner race

(c) Rolling element



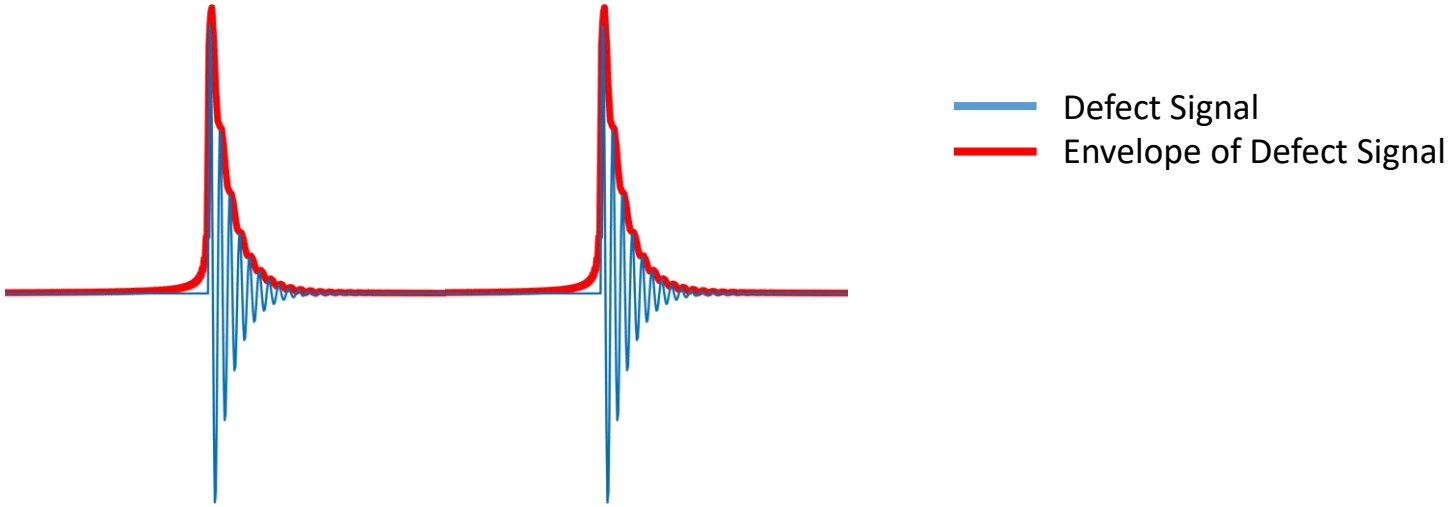
- One of the most widely element in rotating machinery
- Their failure is the most important cause of machinery breakdowns
- Correctly detecting and diagnosing bearing faults at stages prior to their complete failure is crucial
- Avoids potential catastrophic damage not only to the apparatus but also to the personnel

* Li, K., Ping, X., Wang, H., Chen, P. and Cao, Y., 2013. Sequential fuzzy diagnosis method for motor roller bearing in variable operating conditions based on vibration analysis. *Sensors*, *13*(6), pp.8013-8041

Rolling Element Bearings

Vibration Based Diagnosis:

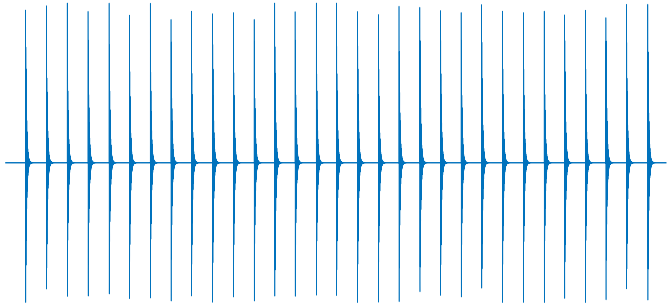
- **Localized defects:** an impact is generated each time the defect is engaged and consequently the bearing and machine structure are excited



- **Envelope analysis:** has been used for long time to extract the bearing defect frequencies

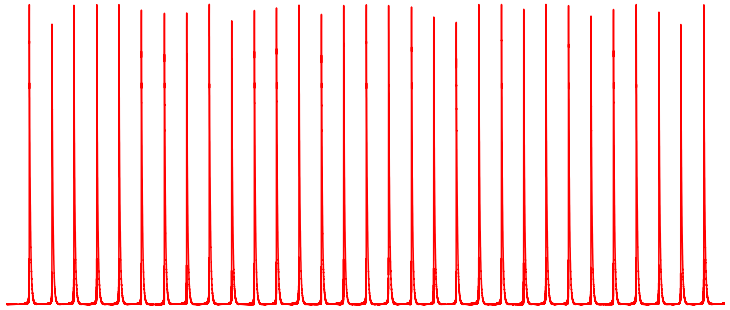
Rolling Element Bearings

Time signal



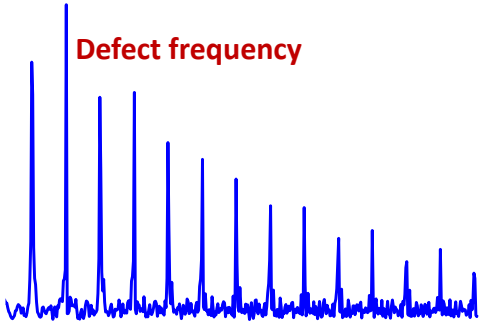
t (sec)

Envelope signal



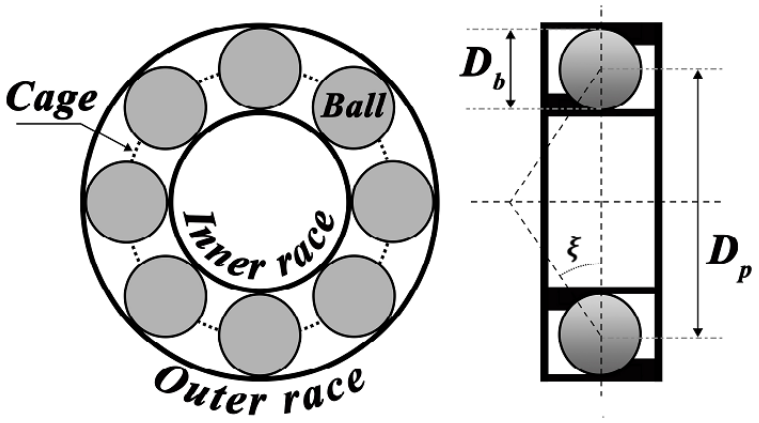
t (sec)

Frequency Domain

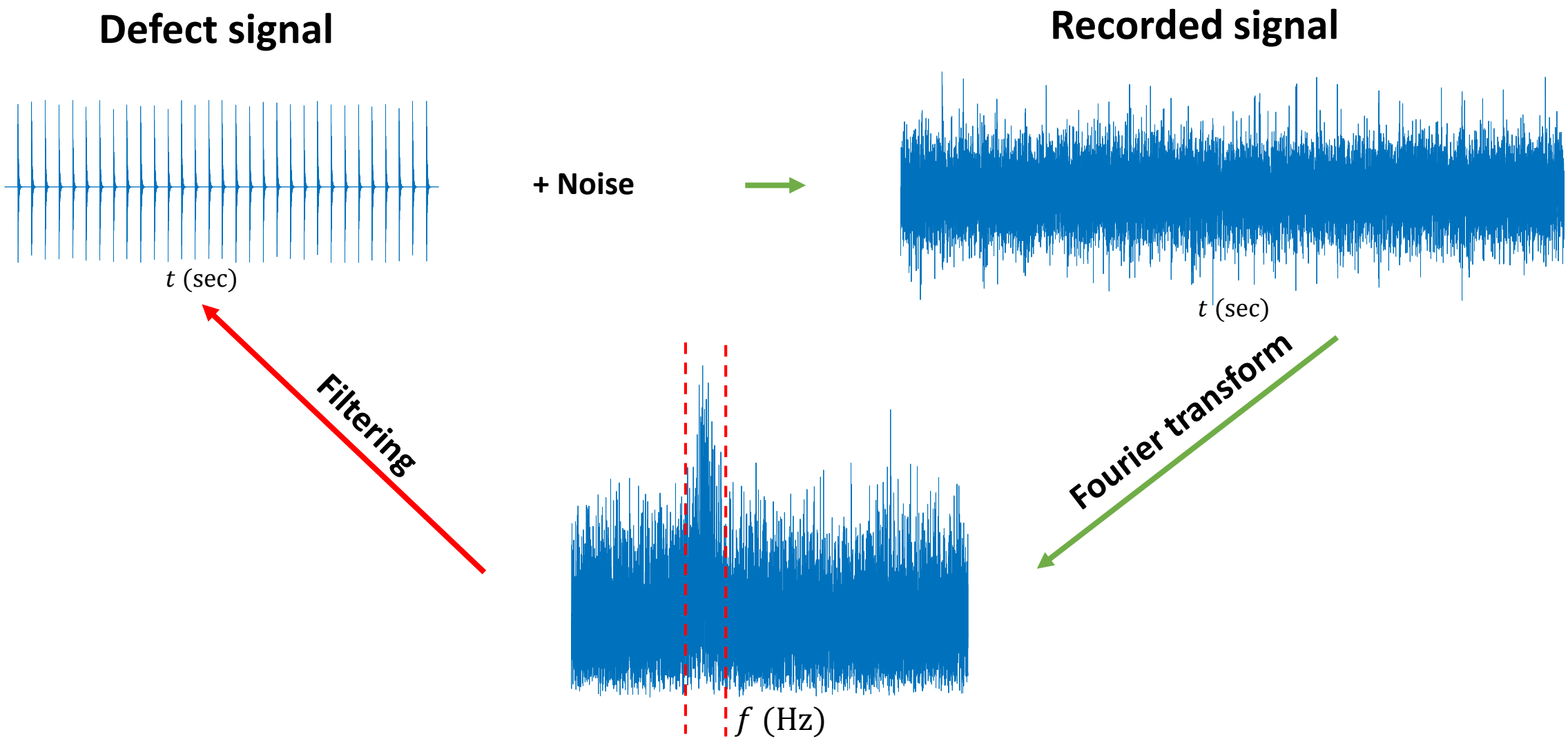


f (Hz)

- Ballpass frequency, outer race (BPFO): $$f_{bpfo} = \frac{N_b}{2}(f_o - f_i)(1 - \frac{D_b}{D_p}\cos\xi)$$
- Ballpass frequency, inner race (BPFI): $$f_{bpfi} = \frac{N_b}{2}(f_o - f_i)(1 + \frac{D_b}{D_p}\cos\xi)$$
- Ball (roller) spin frequency (BSF): $$f_{bsf} = \frac{f_o - f_i}{2}\frac{D_p}{D_b}(1 - (\frac{D_b}{D_p}\cos\xi)^2)$$



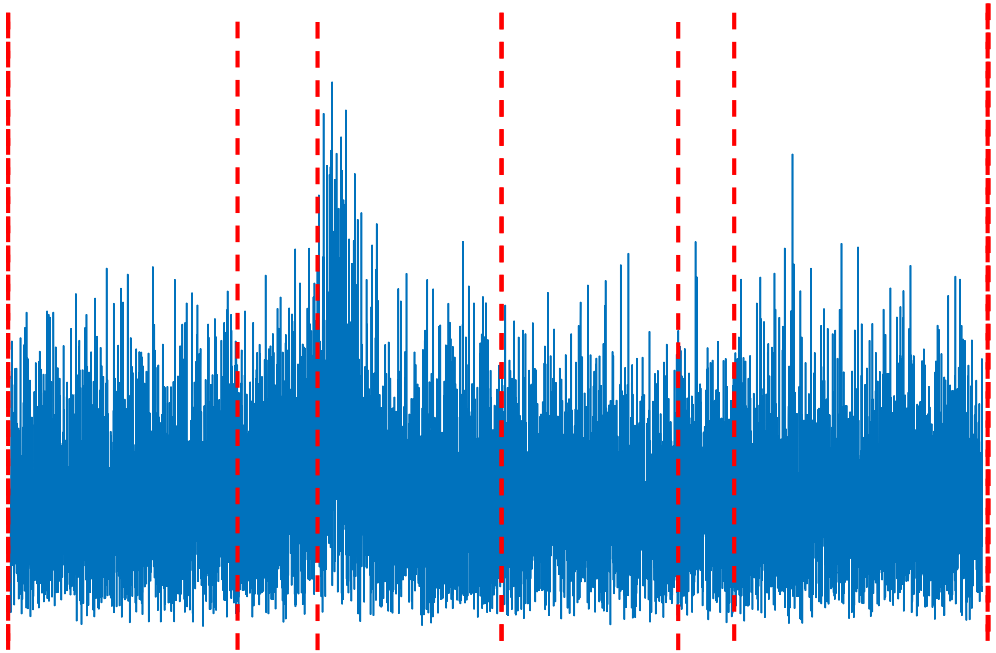
Introduction

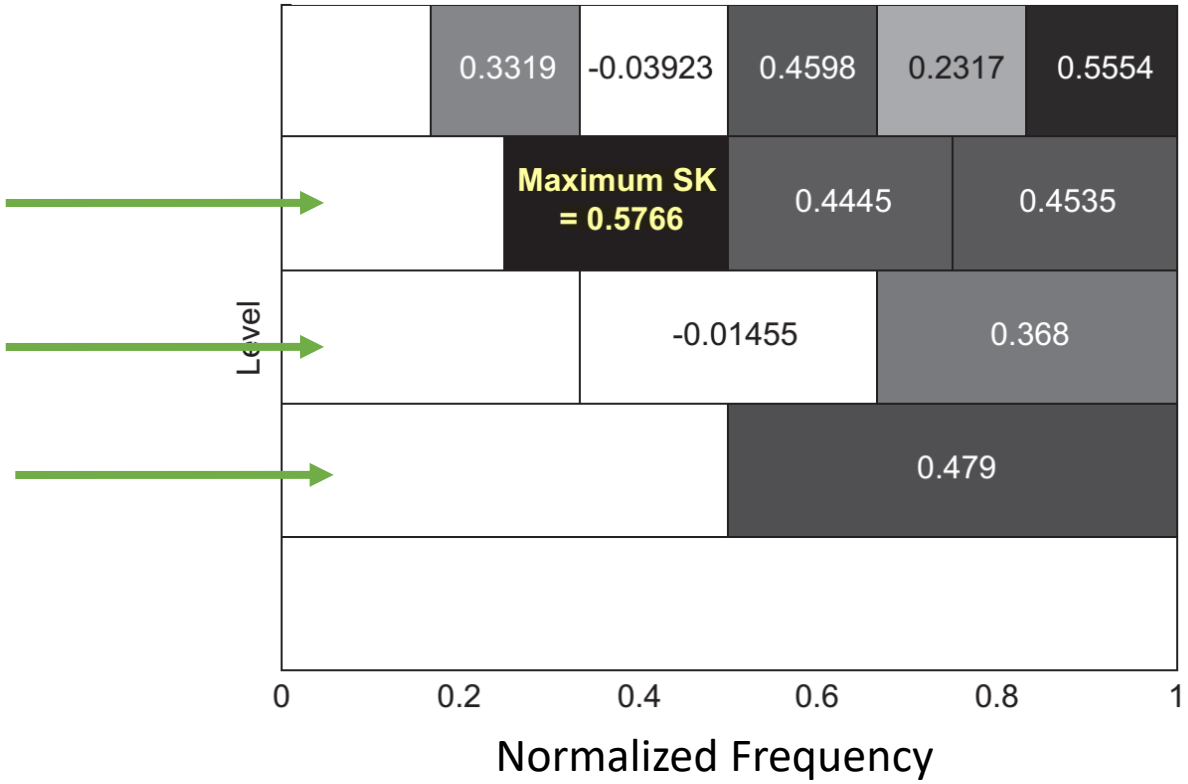


- **Main challenge:** finding the most suitable frequency band for demodulation

Spectral kurtosis and Kurtogram

- **Spectral kurtosis (SK)** has been a significant step to unravel this problem
  - Find the most impulsive frequency band



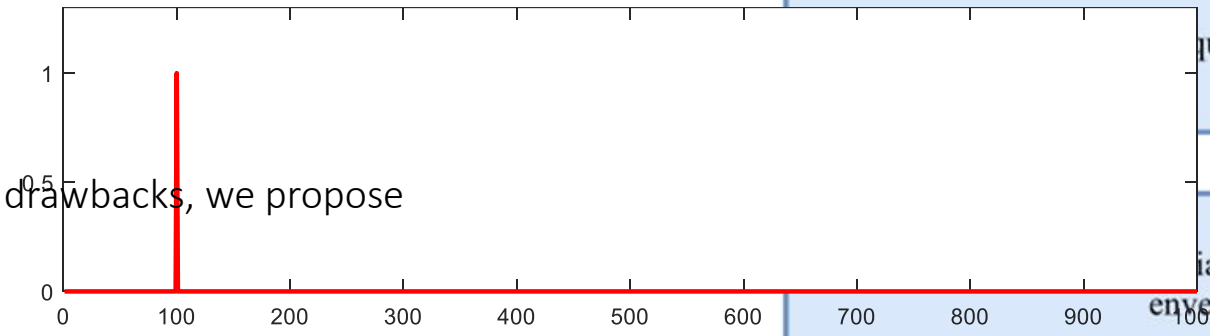


Quantify the impulsivity: $\text{Kurtosis} = \dfrac{\Sigma\, x_i^4}{[\Sigma\,(x_i^2)]^2}$

Proposed Method

Flowchart of the proposed method in 4 steps

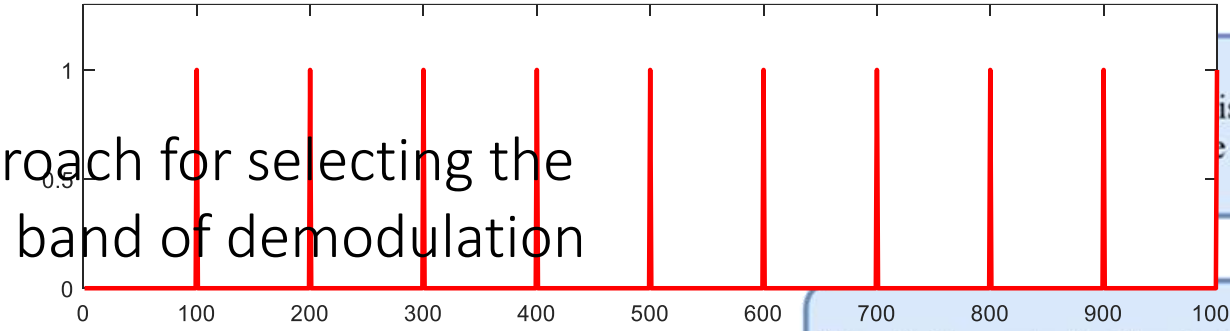
Fast Kurtogram is vulnerable to **impulsive noise** which makes it more sensible to individual impulses than to series of transients

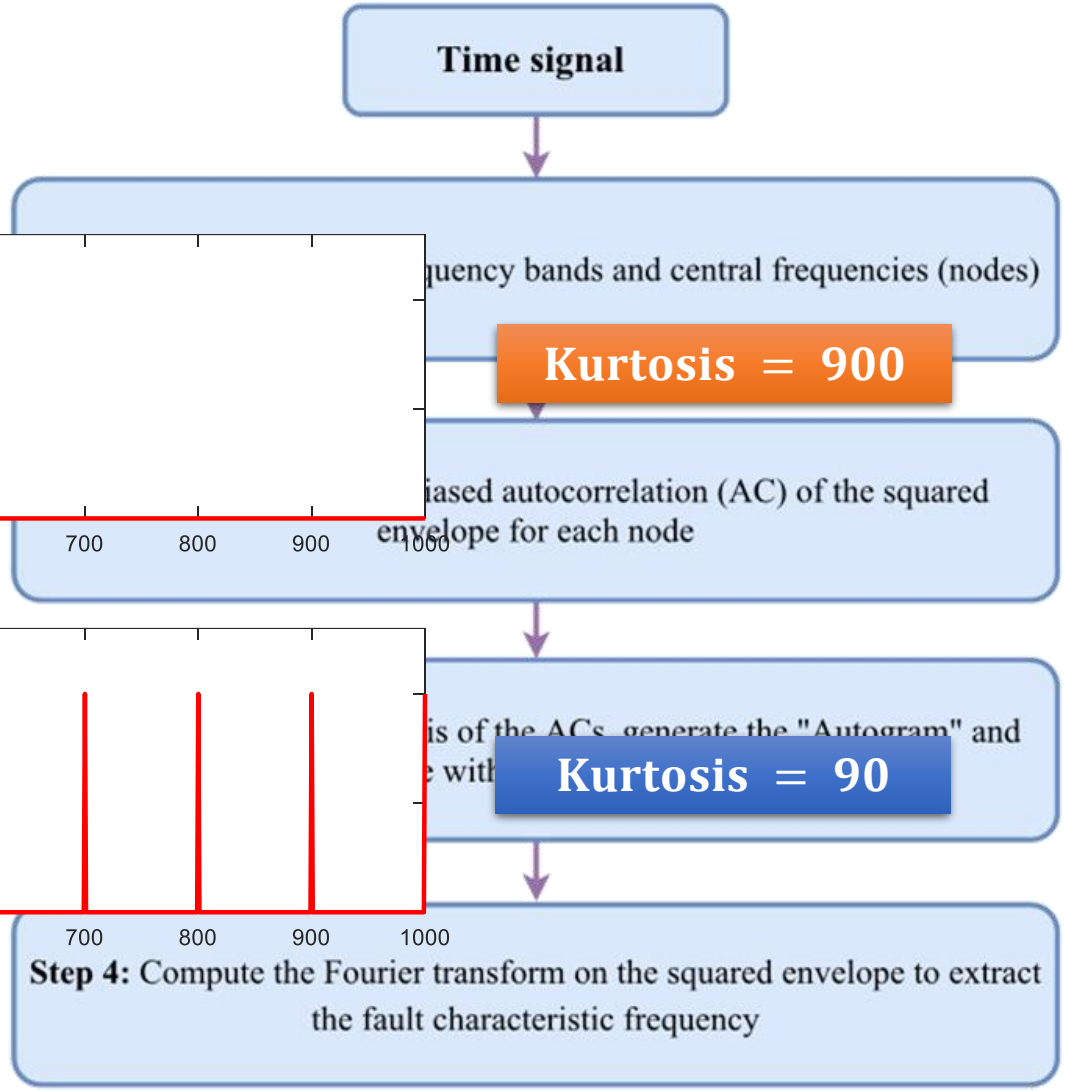


To overcome the mentioned drawbacks, we propose

Autogram:

An alternative approach for selecting the optimal frequency band of demodulation





Step 1

- **Maximal overlap discrete wavelet packet transform (MODWPT)**
  - Split a signal in different frequency bands and central frequencies (node)
- **Differences with discrete wavelet packet transform (DWPT)**
  - Down-sampling step in DWPT is removed
    - at higher levels the lengths of the coefficient series are much shorter which causes larger estimation error
  - DWPT can be sensitive to the selection of starting point
  - Full length of signal is needed to implement the next steps

Step 2

- **Cyclostationary of order *n***
  - nth order statistics is periodic

$$R_{xx}(t,\tau) = \mathbf{E}\{x(t-\tau/2)x(t+\tau/2)\}$$
$$R_{xx}(t,\tau) = R_{xx}(t+T,\tau),$$

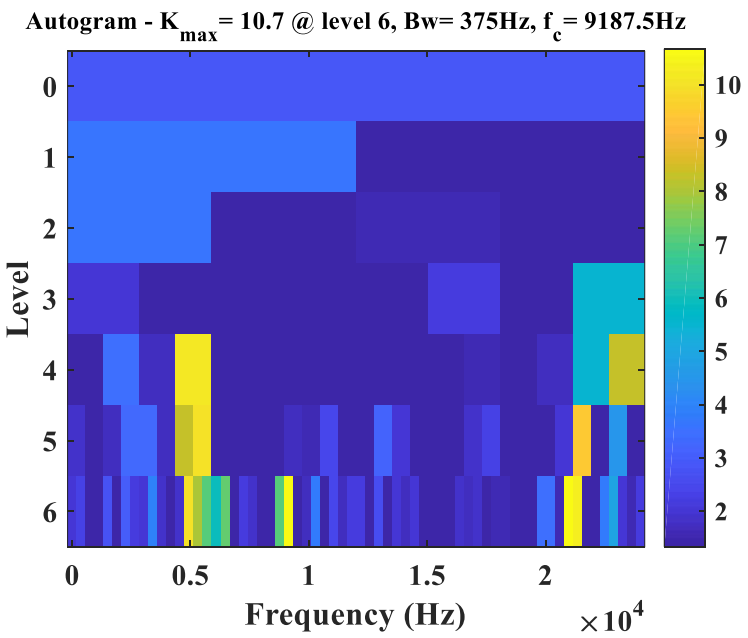
- **Bearing localized faults show high level of 2nd order cyclostationary**

- **Fundamental motivation of this work is to take advantage of this periodicity**
  - instantaneous autocovariance of the signal is periodic (similarly the envelope signal)
  - *unbiased AC* is performed on the squared envelope of the filtered signal for each node

- **This step has the benefits:**
  1. Decreasing the noise level
  2. Removing the random impulsive content and enhancement of periodic part of the signal

Step 4

- **Goal of this step**
  - find the most suitable frequency band for demodulation
  - a proper selection is substantial to have a successful diagnosis
- **Fourier transform** is performed on **envelope** of the filtered signal
- **Autogram**
  - Calculate the kurtosis value of the signals resulting form step 2 (unbiased autocorrelation of the squared envelope)
  - All kurtosis values, similar to Kurtogram, are presented in a colormap
  - Node with the highest kurtosis is considered for further computation



- Extract the fault characteristic frequency
- Diagnose type of the faults

Results and Discussion

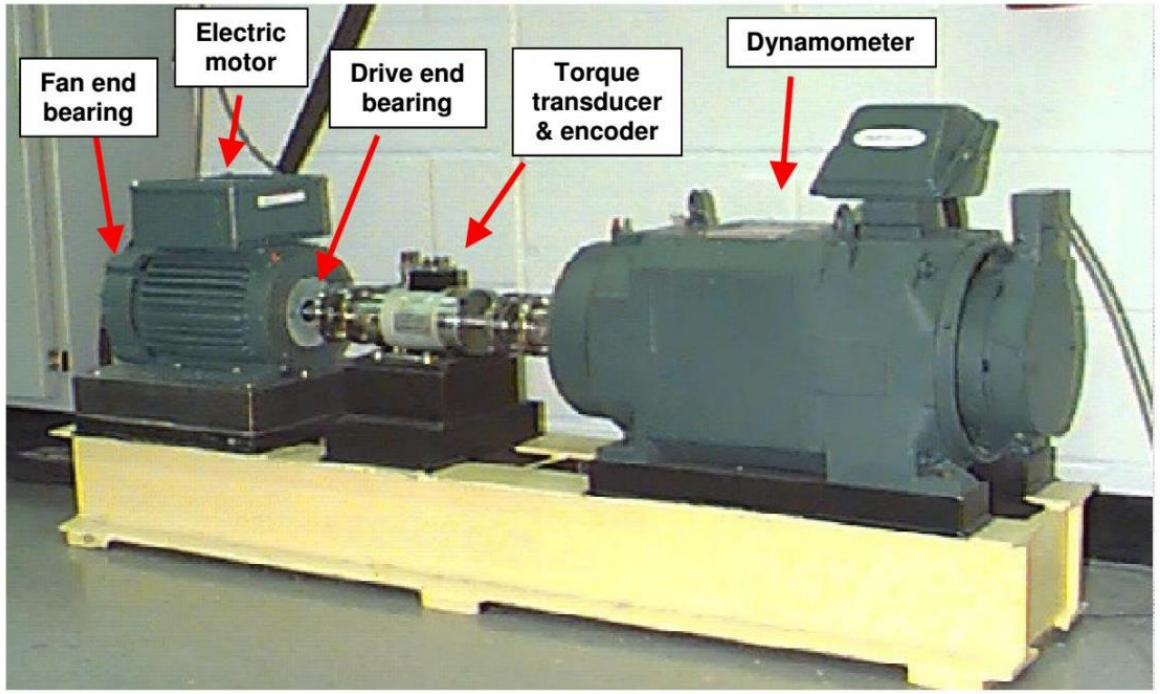
- Two data sets provided by the Case Western Reserve University (CWRU) Bearing Data Center as a standard reference

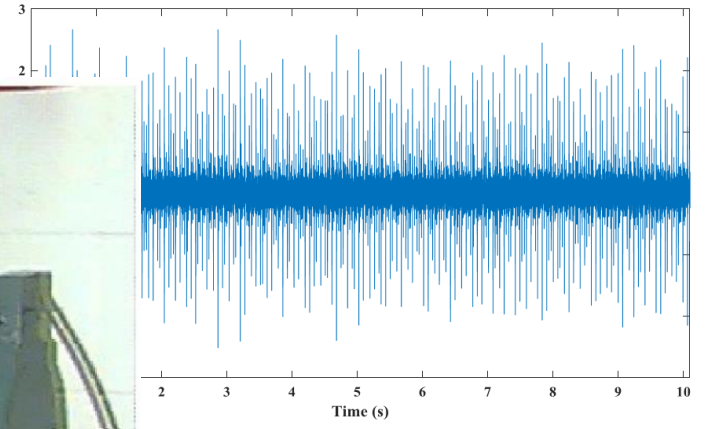
Case 1:

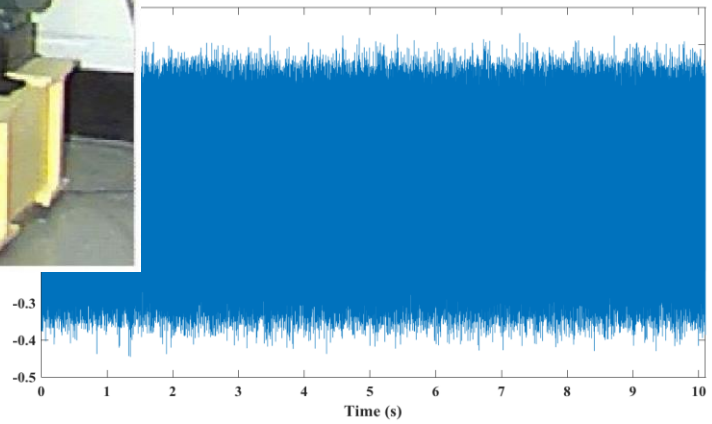
- Inner race def
- Many defect r
  the time wave

Case 2:

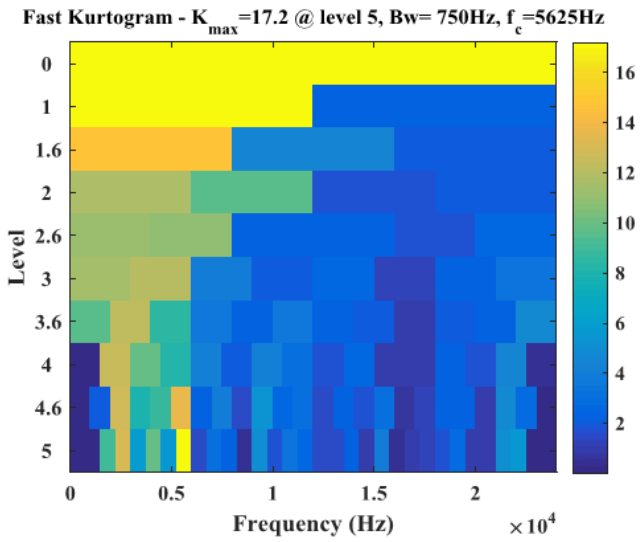
- Rolling eleme
- No defect trar
  waveform



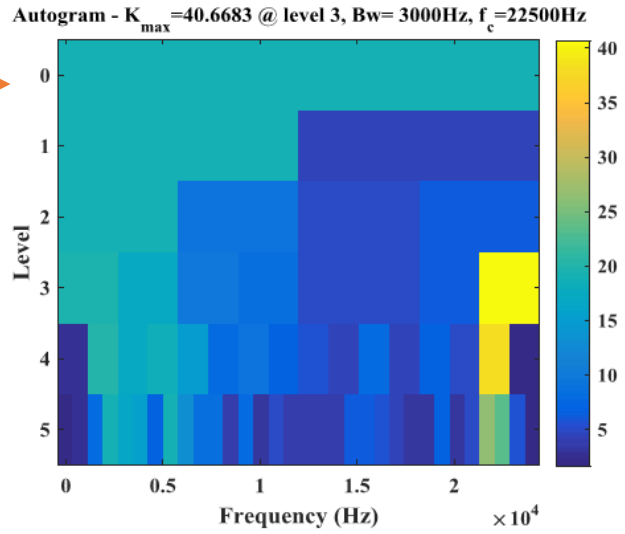




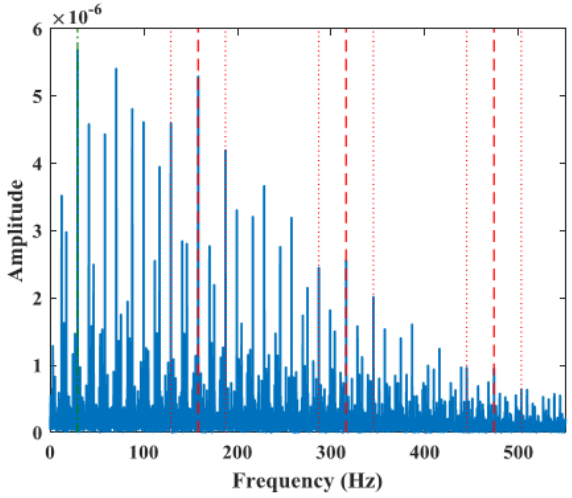
Autogram: Case 1



Fast Kurtogram vs **Autogram**

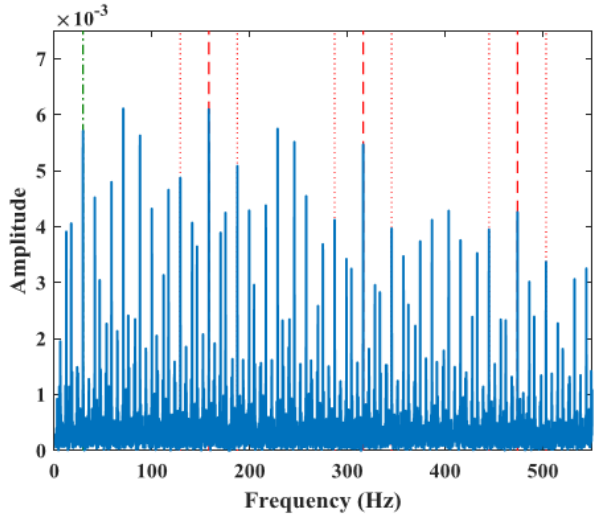


5	**Level**	3
5625 Hz	**Center frequency**	22500 Hz
750 Hz	**Bandwidth**	3000 Hz



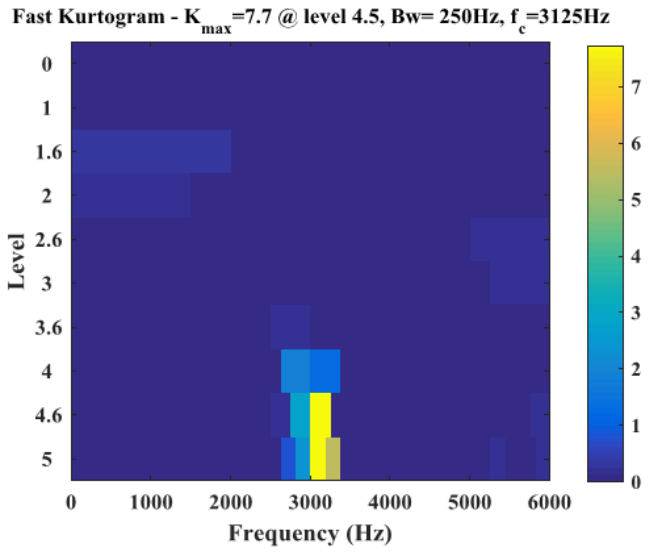
squared envelope spectrum of the filtered signals

Red dash-dot line: nominal defect frequency

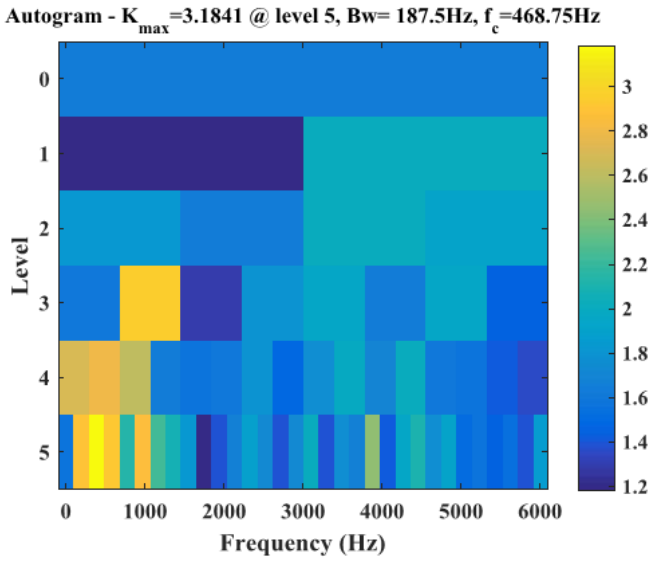


- Different demodulation band
- Successful diagnosis for both method
- Fast Kurtogram selected node also have high kurtosis in the Autogram
- Autogram selected node is not clearly detectable in the Fast Kurtogram

Autogram: Case 2

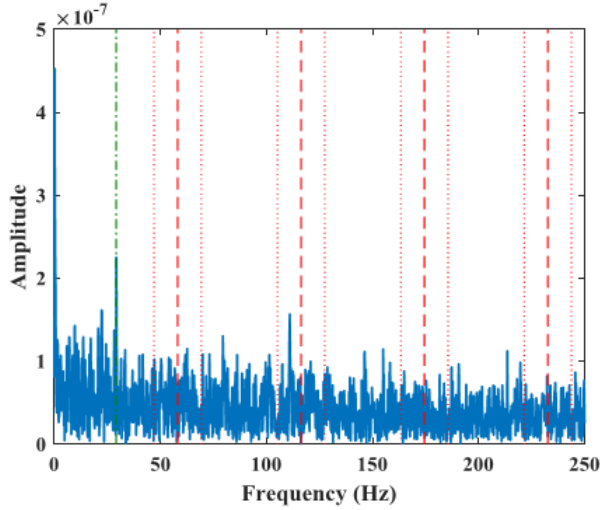


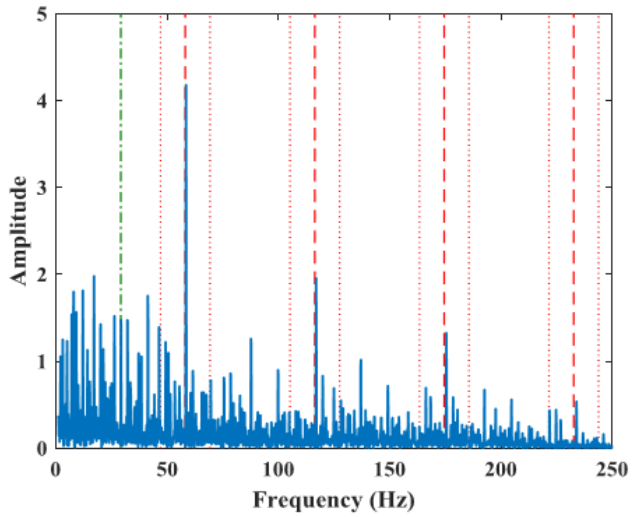
Fast Kurtogram vs Autogram



4.5	**Level**	5
3125 Hz	**Center frequency**	469 Hz
250 Hz	**Bandwidth**	188 Hz

squared envelope spectrum of the filtered signals





- Fast Kurtogram does not detect the bearing fault
- Autogram: harmonics of ball spin frequency (BSF) can be detected
- Another frequency band can be identified in the right side of the Autogram
- Frequency band associated to the impulsive noise has lower kurtosis value in Autogram

Autogram: Case 2

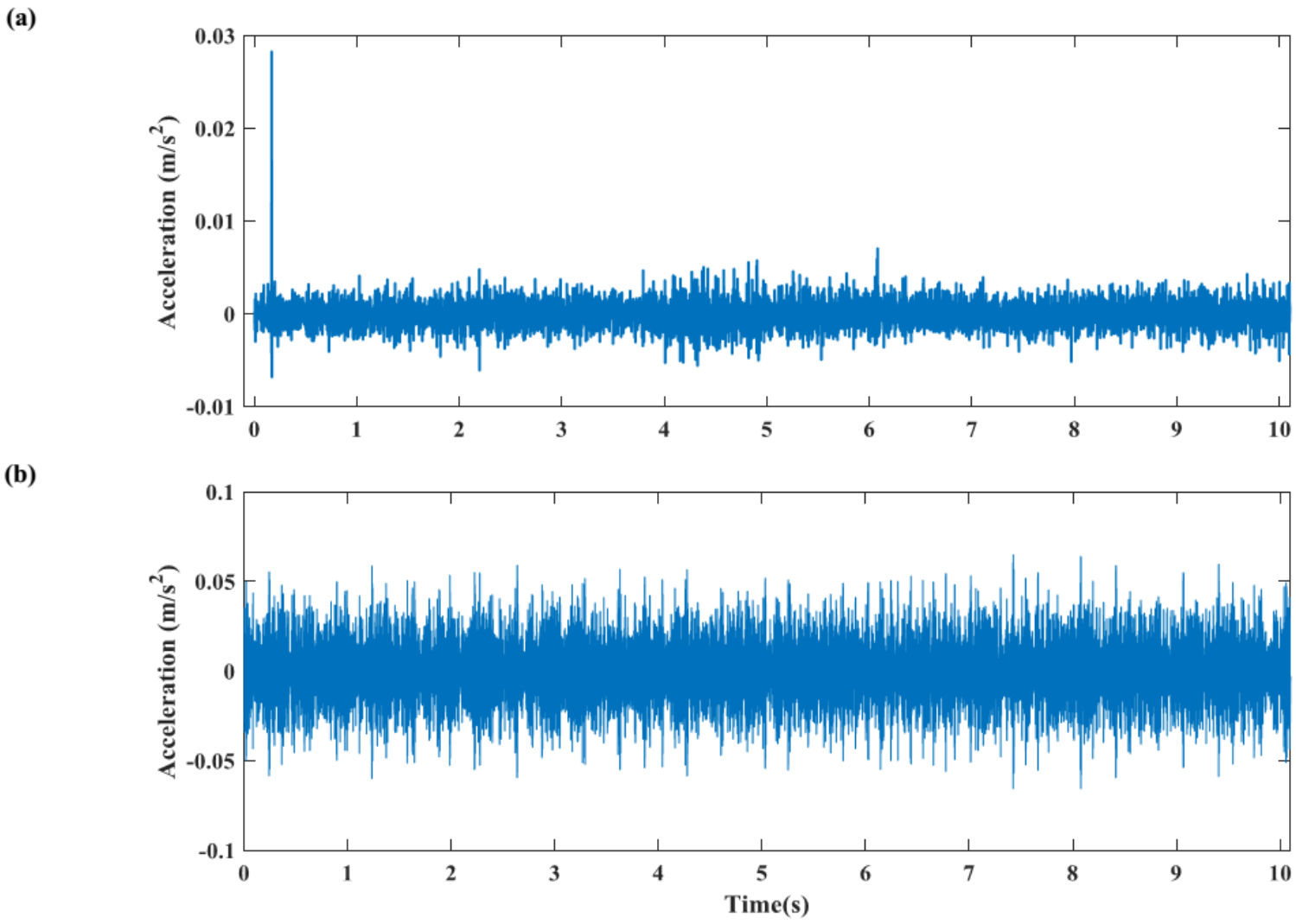
Filtered signal associated with the node with the highest kurtosis in the

(a) Fast Kurtogram

- vulnerable to impulsive noise

(b) Autogram

- a series of transients is present



Conclusion

POLITECNICO DI TORINO

- **Developed a planetary gear train lumped parameter model**
  - To investigate the gears and bearings interaction in presence of faults
- **Proposed a new enhanced Fast Kurtogram (Autogram)**
  - A method to find the proper frequency band of demodulation for bearing faults diagnosis specially in presence of impulsive noise
- **Two bearing data sets were studied**
  - The results show the improved capability of the Autogram over Fast Kurtogram in dealing with signals with impulsive noise

Future Work

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- **Modify the Model to Take Into Account Flexibility Of Gearboxes Casings and Slippage in Bearings**
- **A new method for REBs diagnosis by considering the whole frequency band**

Publication

Journal Papers

1- Moshrefzadeh A, Fasana A "The Autogram: an effective approach for selecting the optimal demodulation band in rolling element bearings diagnosis" *Mechanical Systems and Signal Processing (submitted)*

2- Moshrefzadeh A, Fasana A "Planetary gearbox with localized bearings and gears faults: simulation and time/frequency analysis" *Meccanica, 2017*

Conference Paper

1- Moshrefzadeh A, Fasana A, Garibaldi L "Using unbiased autocorrelation to enhance kurtogram and envelope analysis results for rolling element bearing diagnostics" *Surveillance 9, International Conference, 2017*

Thanks for Your Attention

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