

Advanced Analytics for Motor Current Signature Analysis: An Overview

By

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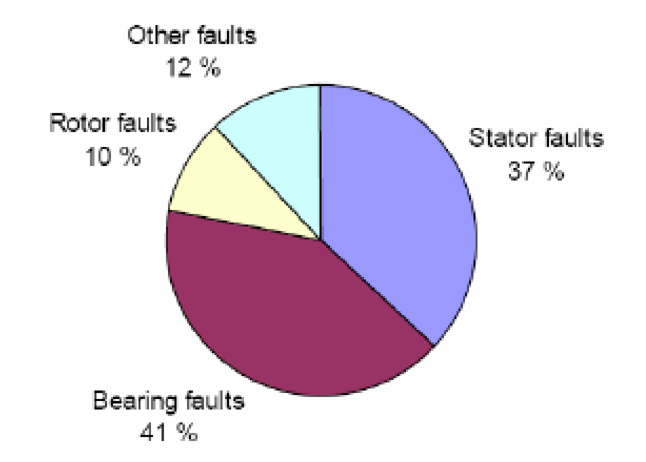
Introduction: Failure Modes

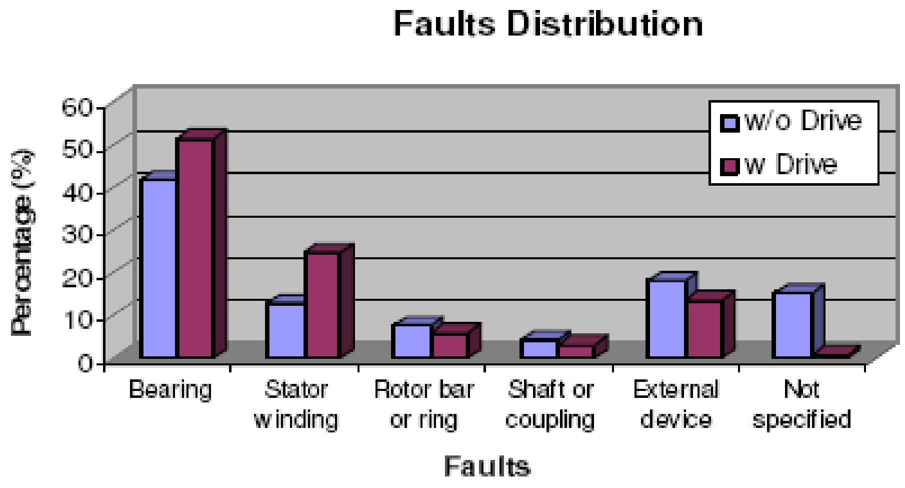
PERCENTAGE OF FAILURES BY MAJOR MOTOR COMPONENT

Major Components	IEEE-IAS [28], [29] % of Failures	EPRI [30] % of Failures
Bearing Related	44	41
Winding Related	26	36
Rotor Related	8	9
Other	22	14

IEEE TIA, 42(2), 2006, Mirafjal et al.



http://www.control.hut.fi/Kurssit/AS74.3115/Materiaali/Material2007/Fault_diagnosis_of_electric_motors_2_slides.pdf

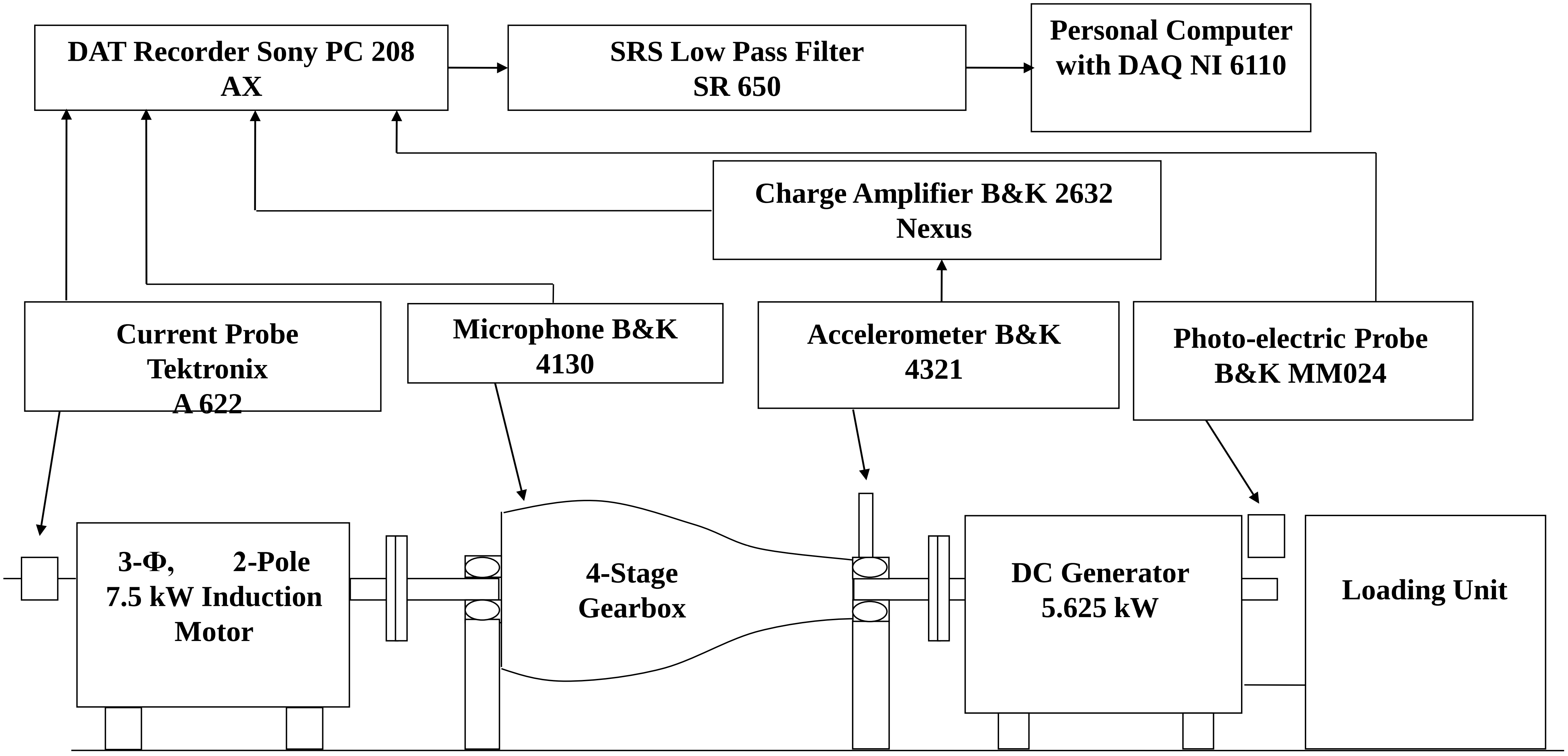


MS Thesis: Ali S. Al-Sahrani: Oregon State University

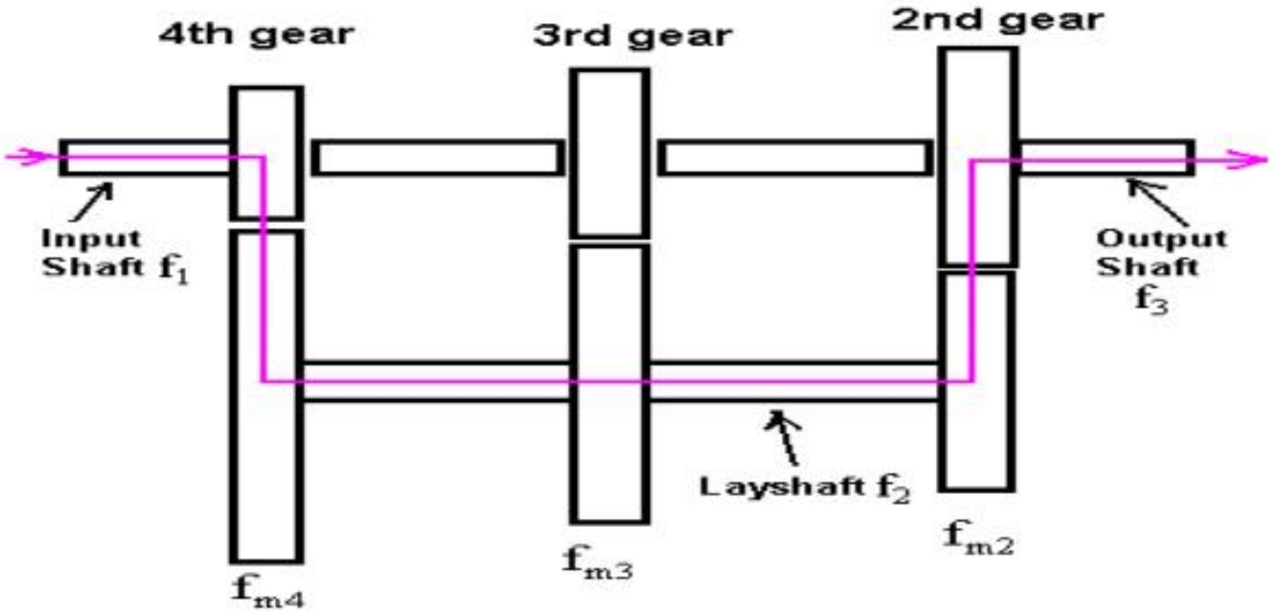
- Bearing Fault
- Stator fault:
  - Stator Insulation / Winding Short Circuit /Voltage Unbalance
- Rotor Fault:
  - Broken rotor bar and Rotor end ring failure
- Motor Fault
  - Air-gap
    - Static eccentricity
    - Dynamic eccentricity

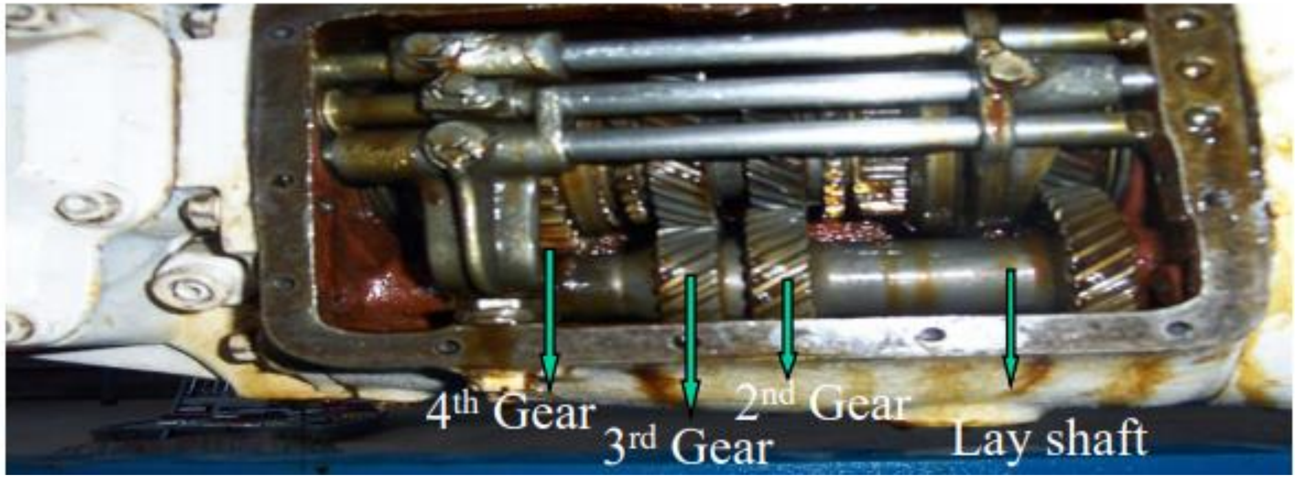
Objective: Detect Mechanical Failures using Motor Current

Introduction: Experimental Set-up



Automotive Transmission Gearbox





Defects in 2nd gears

Two teeth missing

in 2nd main gear (d4):

Two teeth cut in

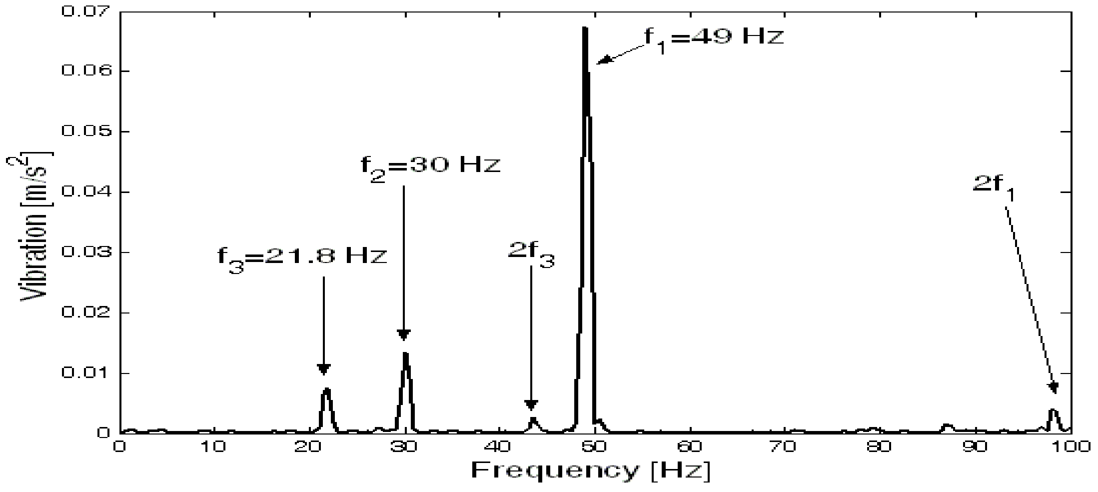
Die sinking EDM

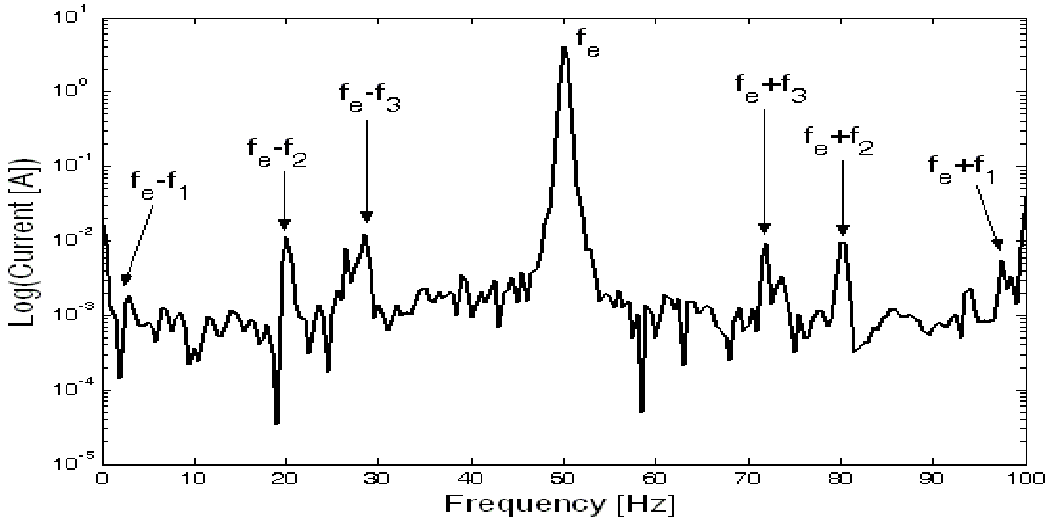
Results: FFT Analysis (Low frequency components)

Normal Gear

Vibration Signals

Current Signals



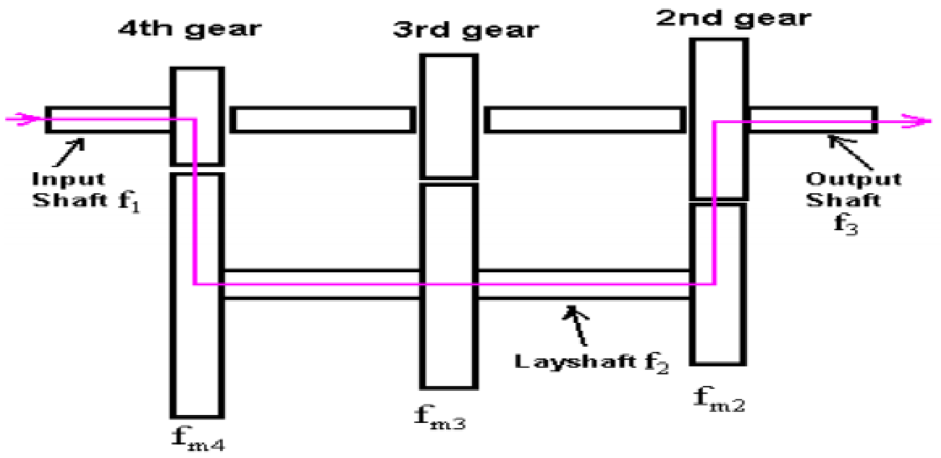


f_1: Input shaft speed 49 Hz

f_2: Layshaft speed 30 Hz

f_3: Output gear shaft speed 21.8 Hz

f_e: Current Line Frequency 50 Hz



All rotating shaft frequency appear as sidebands across line frequency

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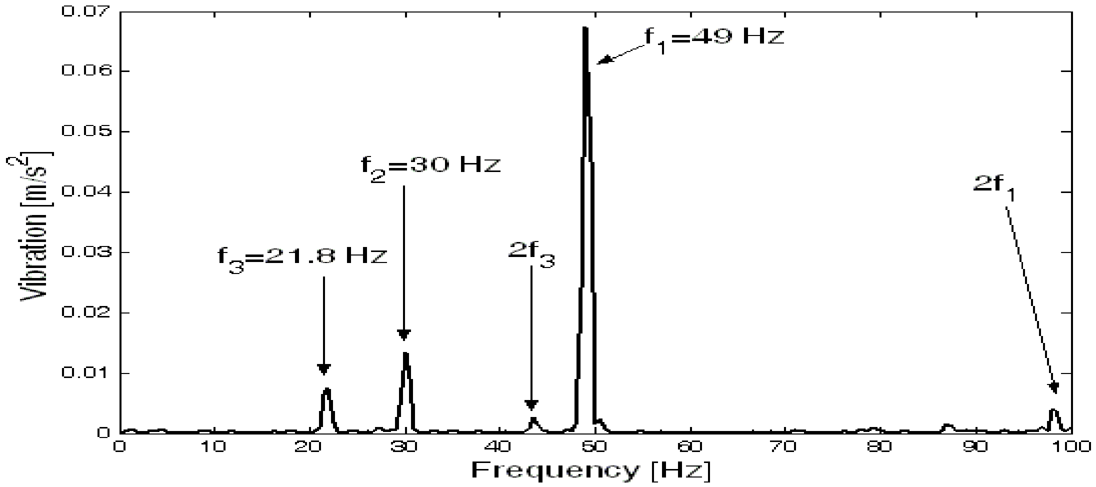
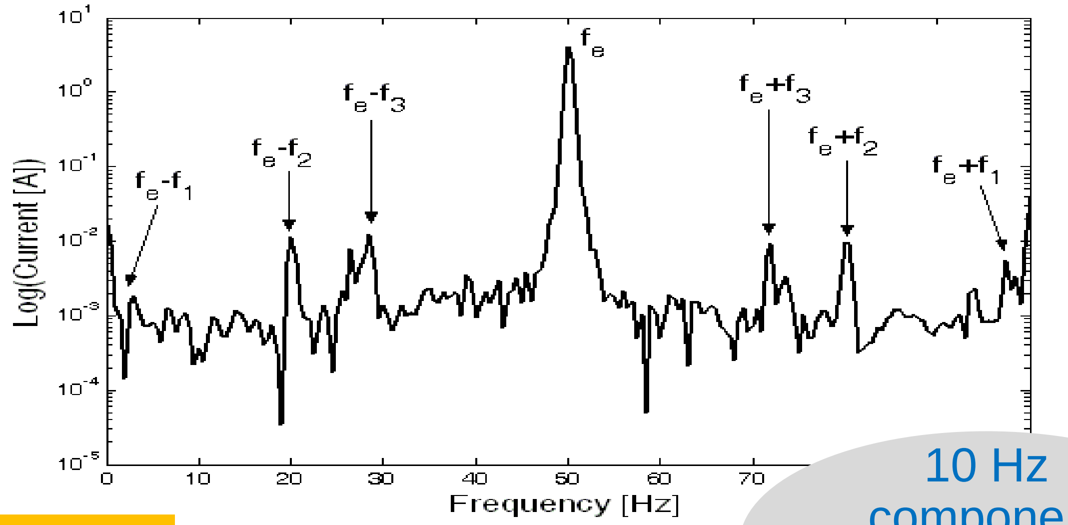
Results: FFT Analysis (Low frequency components)

Vibration Signals

Normal Gear

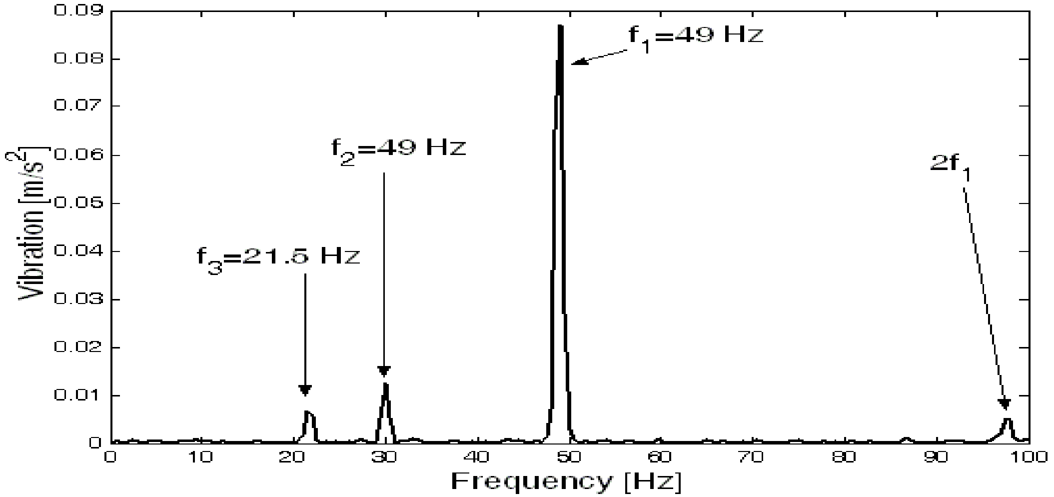
Current Signals

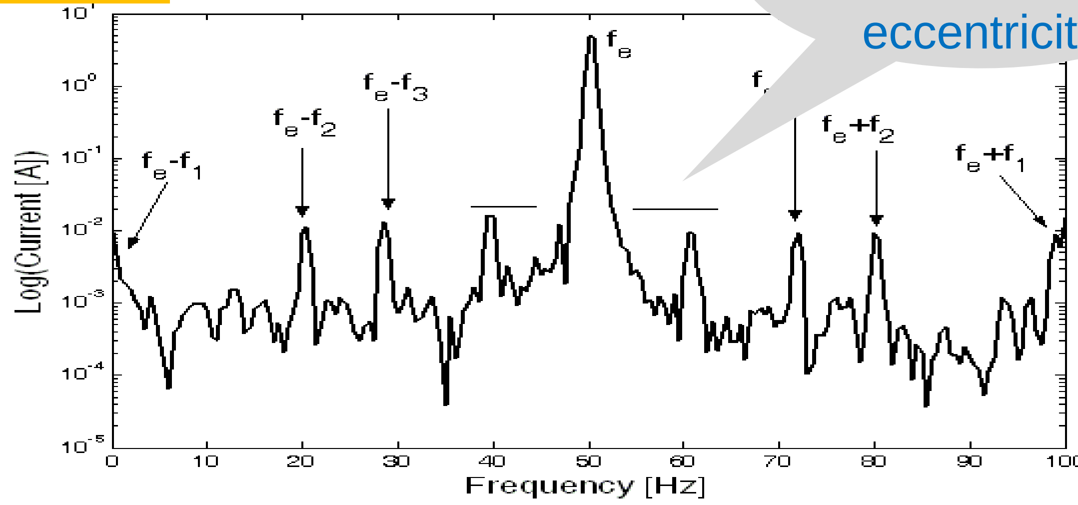




10 Hz component due to eccentricity

Defective Gear





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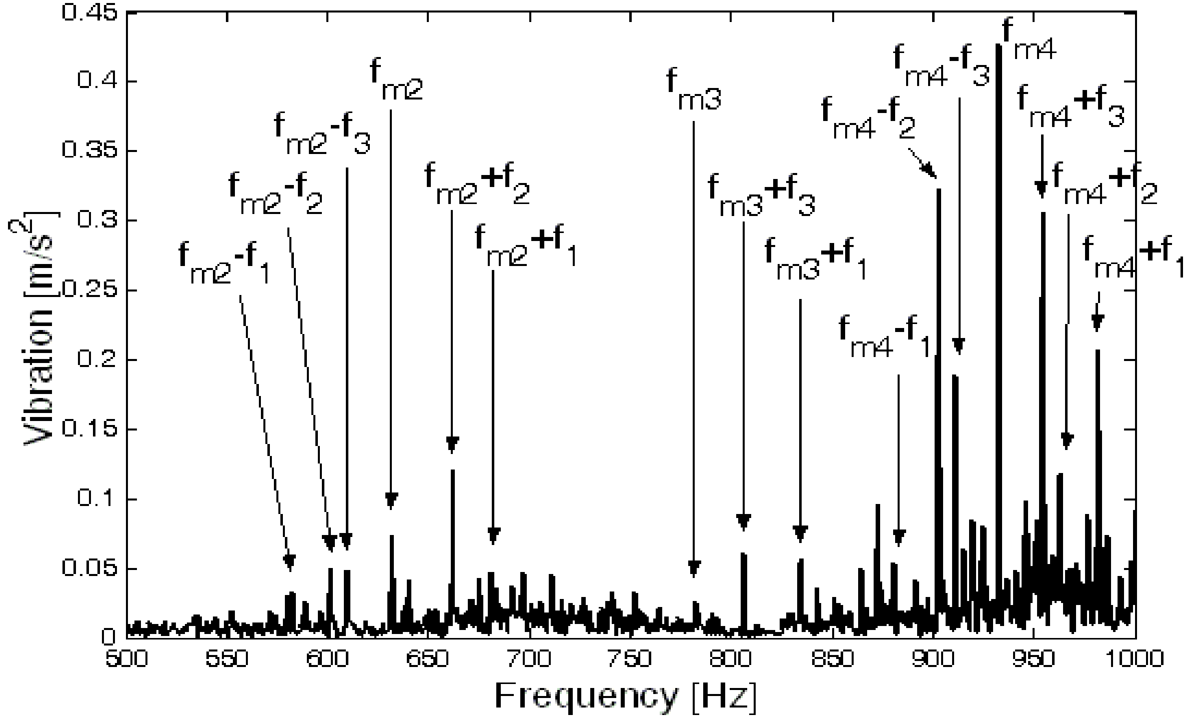
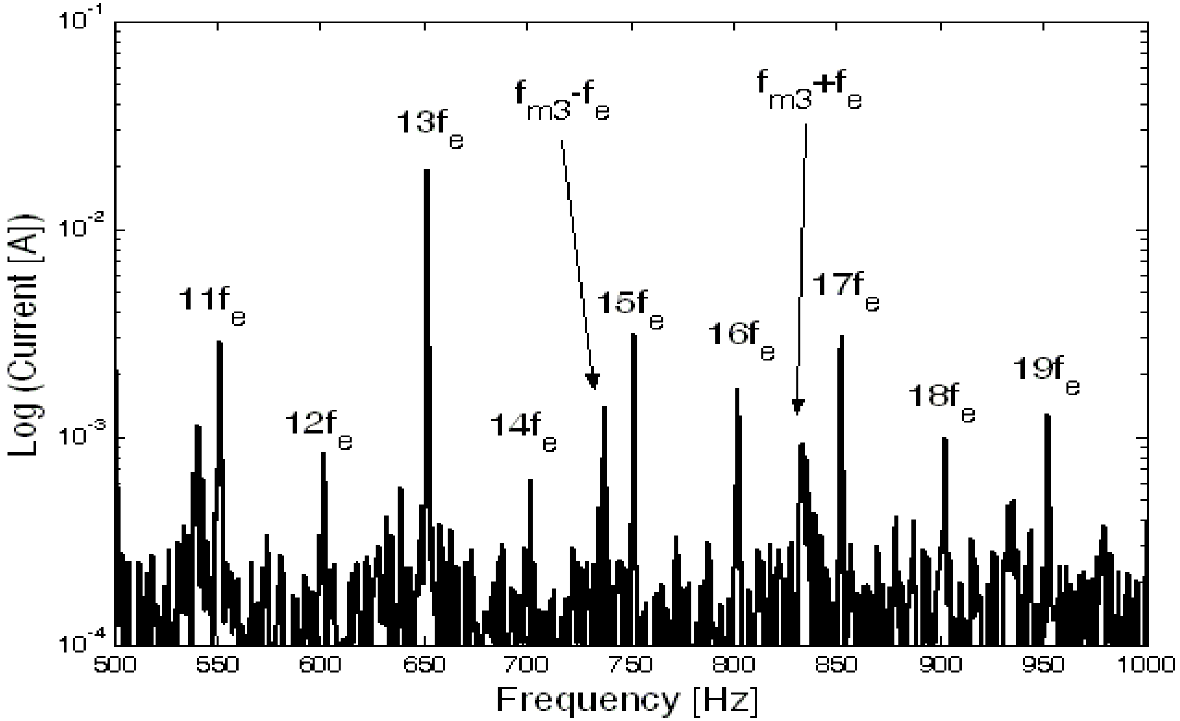
Results: FFT Analysis (High Frequency components)

Normal Gear

Vibration Signals



Current Signals



- The GMFs and its sidebands of shaft frequencies are traced in vibration and noise signals;
- GMF are not traced in the current signal due to noise and dominant line frequency

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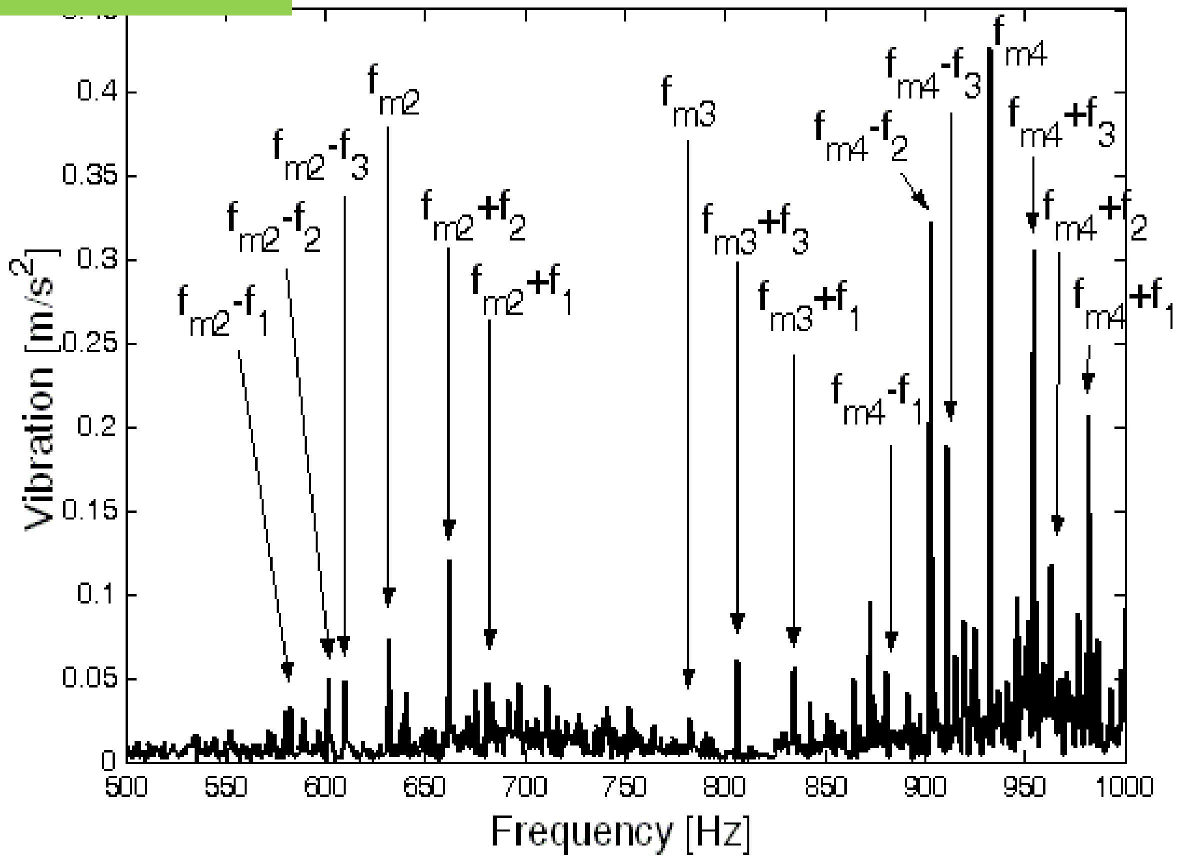
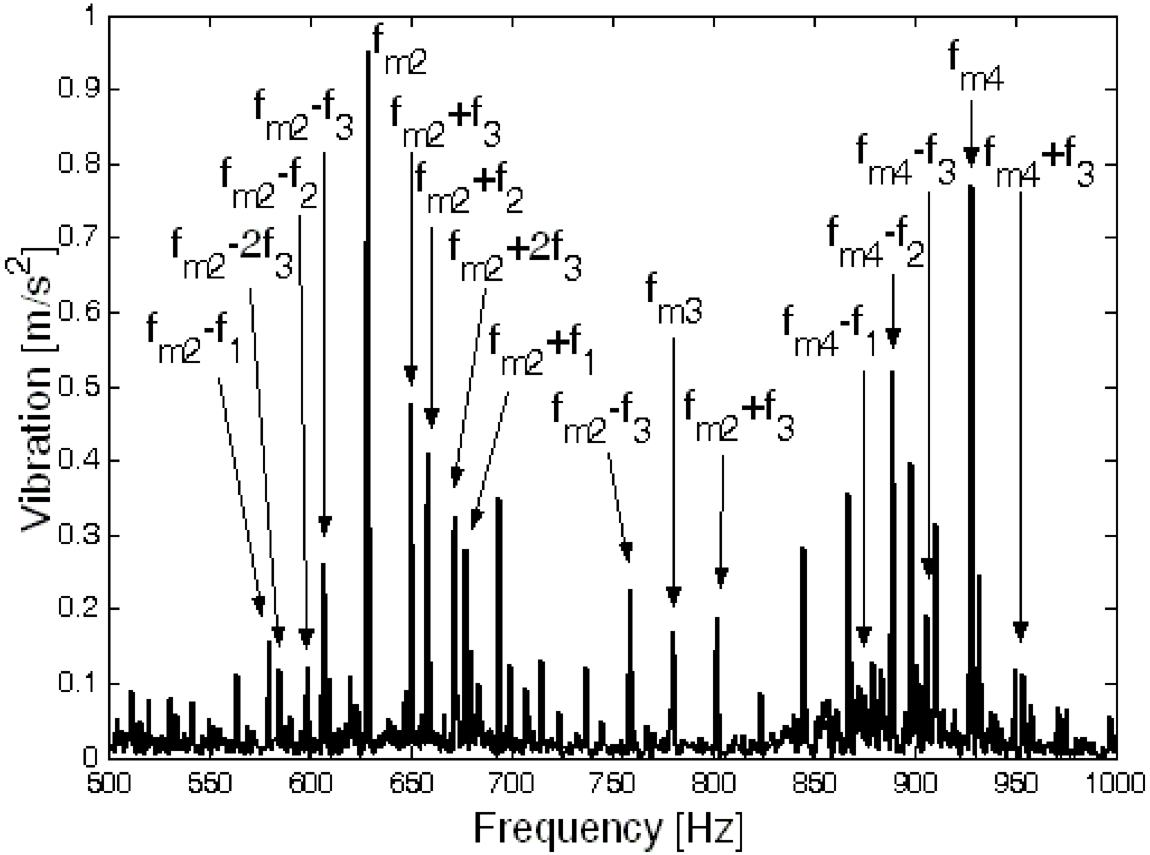
Results: FFT Analysis (High Frequency components)

Vibration Signals

Normal Gear



Defective Gear



- For vibration spectra of healthy gears, 4th GMF is predominant; whereas with defects in 2nd gear, 2nd GMF gains energy
- GMF are not traced in the current signal

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Summary: FFT Analysis

- In vibration signals
  - 2nd GMF and its sidebands of output shaft frequency can detect defects
- In current signals
  - Each low frequency component appears as sidebands across line frequency
  - Tracking supply line frequency can detect defects
  - GMF could not be detected in current signals due to
    - Poor signal to noise ratio
    - Dominant line frequency and its harmonics
- Therefore, another technique ‘Demodulation’ is applied to the current signal

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Amplitude Demodulation

- **Advantages**
  - Eliminate any dominant carrier frequency ($f_{Carrier}$)
  - Highlights the defect related modulating frequencies ($f_{Modulating}$)
  - Assumes that fc > fm
  - The carrier frequency for Motor Current Signals is Line frequency
  - Improves signal to noise ratio.
  - Helps to differentiate between steady and fluctuating load conditions.

- **Methods:**
  - Square Law Demodulator [Pillay and Zu]:
    1. Square the signal

$$x^2(t) = (A+m)^2 \cos^2 \omega_m t$$
$$= (A+m)^2 \left(\frac{1-\cos 2\,\omega_m t}{2}\right)$$

    2. Apply a low pass filter to remove second harmonic of carrier frequency.
    3. Square root operator will produce the modulating signal
  - As applied by C.Kar in IEEE TIE Vol 53
    1. Multiply the current signal by cosine of the carrier signal

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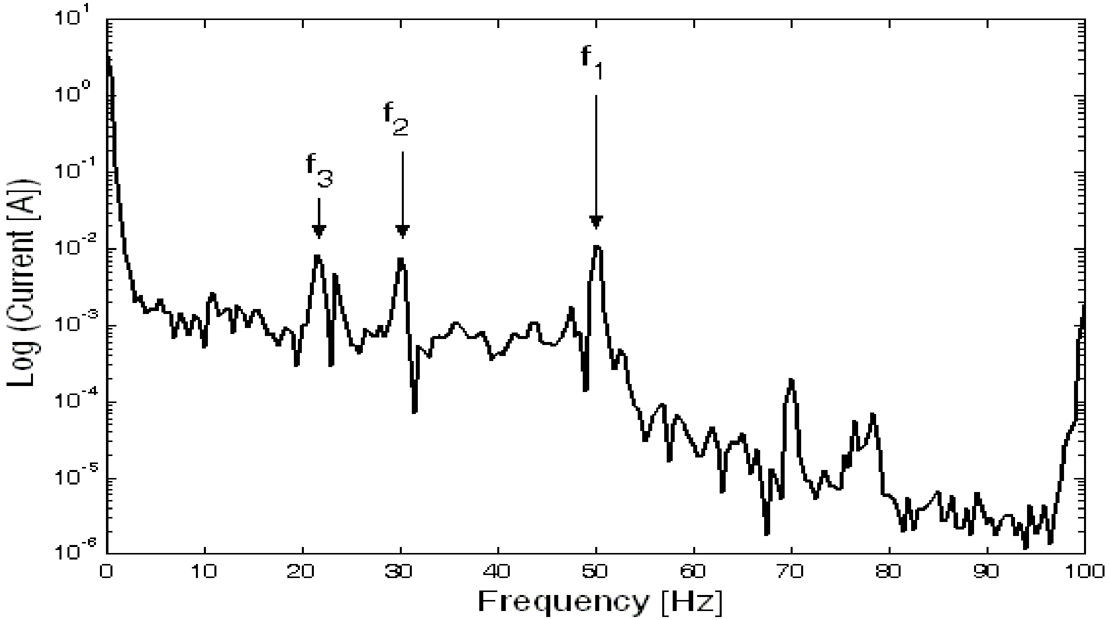
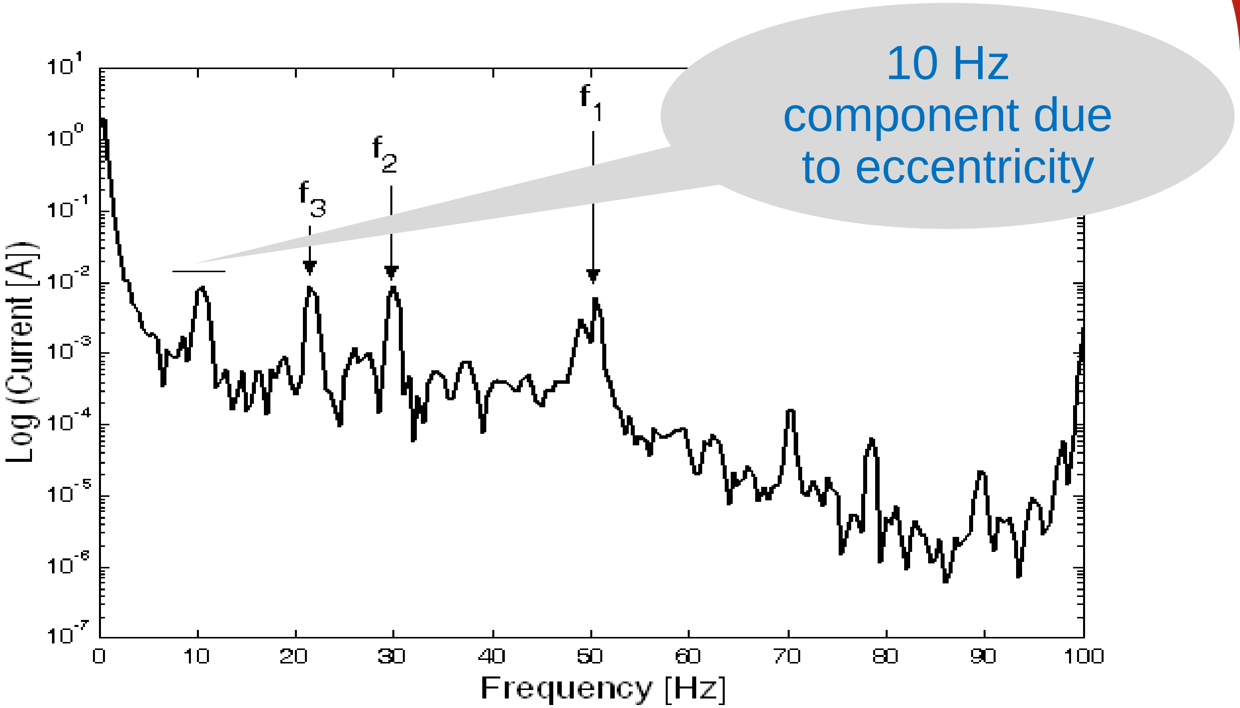
Results: Amplitude Demodulation of Current Signals

Normal Gear

Current Signals

Defective Gear





- **In amplitude demodulated current signals: All rotating shafts can be detected directly;**
- **Amplitude demodulated current signal is unable to detect high frequency GMF due to low carrier frequency**
- **Therefore, Frequency demodulation of current signals are investigated**

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Frequency Demodulation

Assume a signal to be frequency modulated signal

$$y(t) = A\cos\left(2\pi\int_0^t f(\tau)d\tau\right)$$

Apply Hilbert Transform to separate the real and imaginary parts

$$x_a(t) = x(t) + \frac{j}{\pi}\int\frac{x(\tau)}{t-\tau}d\tau$$

Calculate Time-varying phase signal

$$\varphi(t) = \tan^{-1}\left(\frac{\frac{1}{\pi}\int\frac{x(\tau)}{t-\tau}d\tau}{x(t)}\right)$$

Derivation of the phase signal will produce frequency demodulated signal

$$f(t) = \frac{d\varphi(t)}{dt}$$

- **Current Signals:**
  - **Carrier frequency is the line frequency (50Hz)**
  - **Any frequency higher than 50 Hz will appear in frequency demodulated signal**

Ref.: Frequency demodulation through Teager Energy, W-V distribution, Hilbert Transform, WT etc [Patent 5,594,175]

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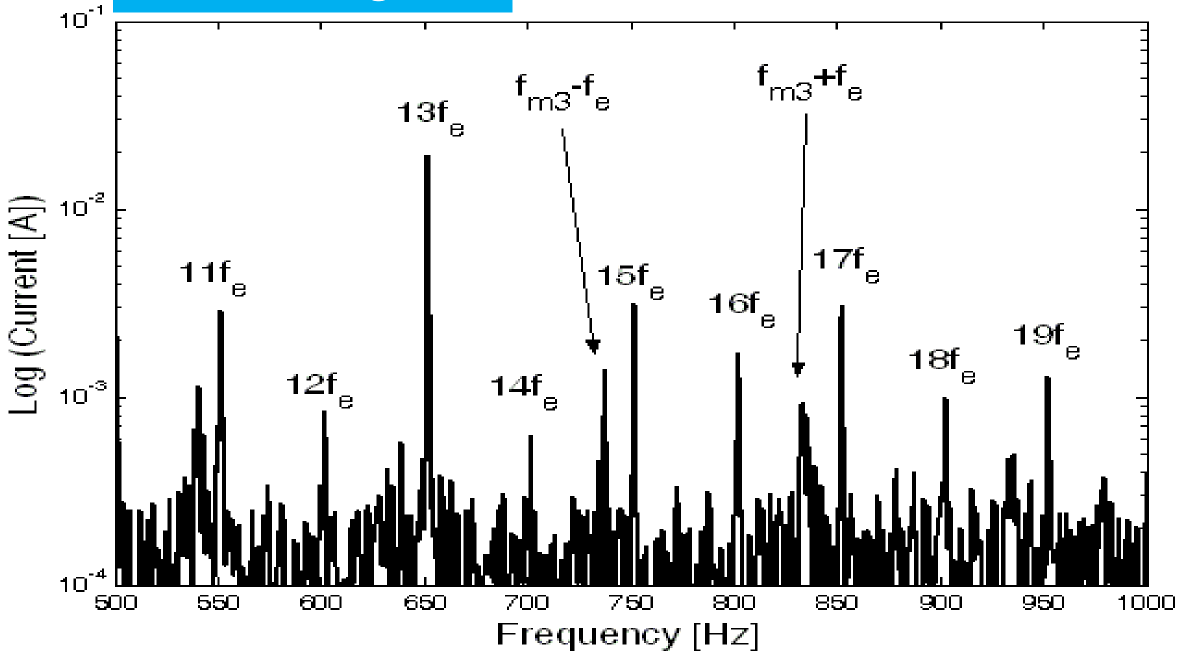
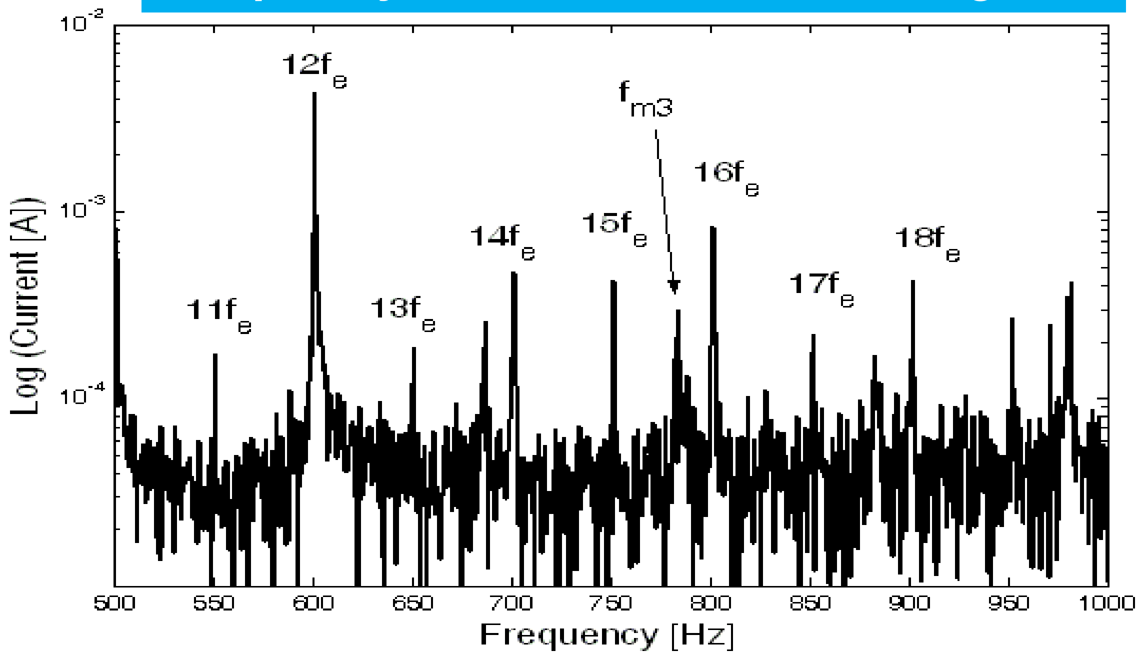
Results: Demodulation of Current Signatures

Normal Gear

Current Signal



Frequency Demodulated Current Signals



- The current signal had dominant odd harmonics
- The frequency demodulated current signal had dominant even harmonics

- The frequency demodulated current signal couldn't detect GMF

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Summary: Amplitude and Frequency Demodulation

- In amplitude demodulated current signals:
  - All rotating shafts can be detected directly;
  - 10 Hz component can be observed for cases of tooth missing which can be attributed to eccentricity;

- Frequency demodulation of current signals is unable to detect GMF due to
  - High frequency noise
  - Dominant even harmonics of line frequency

- Therefore, another technique ‘Wavelet Transform’ is applied to the current signal

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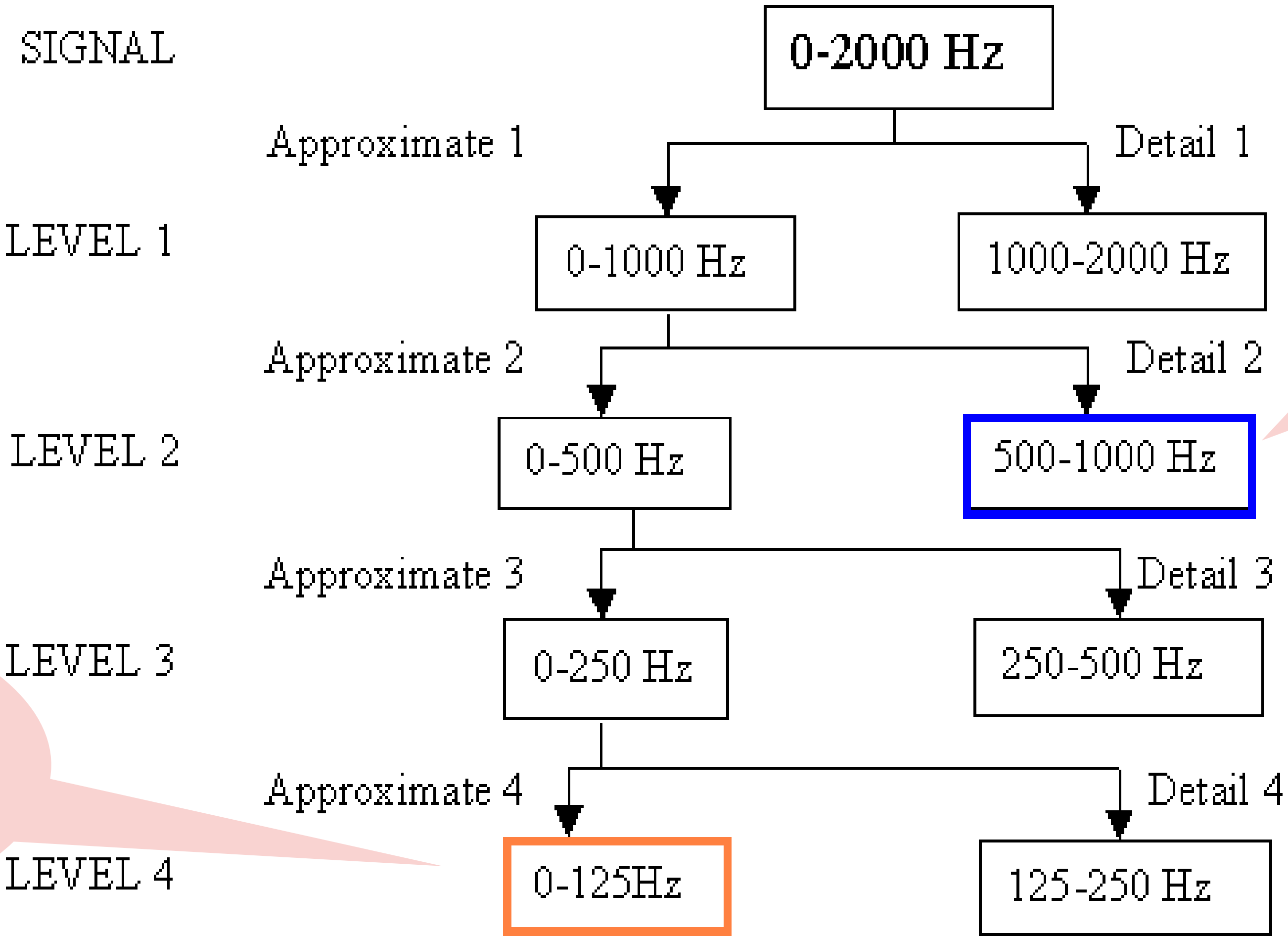
Discrete Wavelet Transform: Decomposition

- **Maximum Frequency content of the signals: 2 KHz;**
- **Db8 wavelet has been considered in the analysis**



Details 2 level contains gear mesh frequencies;

Approximate 4 level contains the supply line frequency in the current signals.

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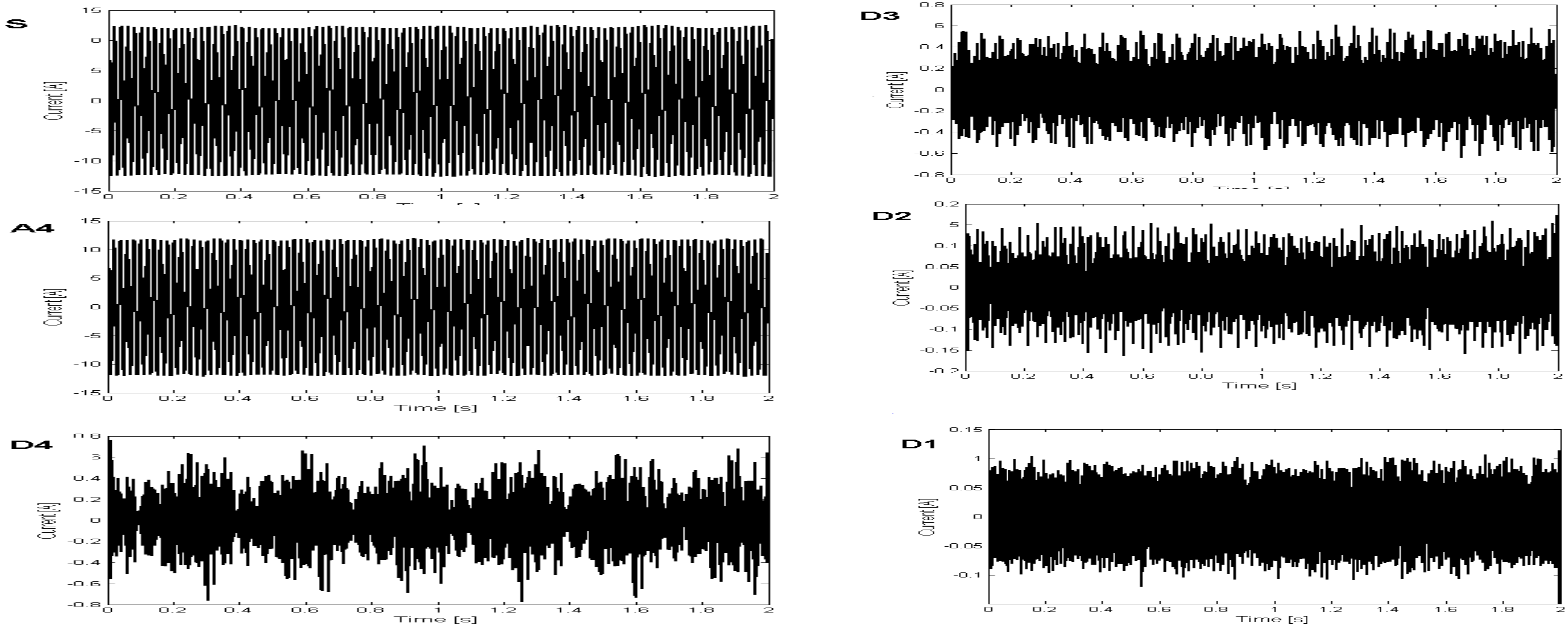
Results : Discrete Wavelet Transform of Current Signals

Defective Gear

Current Signal



An improvement of Wavelet Transform called Multiresolution Fourier Transform is applied to the current signal to detect the frequencies

Multiresolution Fourier Transform

- **Literature Review: Image and Audio Application [Callway]**
- **MFT is a combination of Wavelet Transform and Short-Time Fourier Transform**

$$\hat{x}(t, f, a) = \int_{-\infty}^{\infty} w_a(t-\tau)\, x(\tau)\, e^{-i2\pi f\tau}\, d\tau$$

- **Scaled window**

$$w_a(t) = \sqrt{a}\, w(ta)$$

- **If a single scaled window is used for whole record time, it is equivalent to FFT analysis at that scale.**
- **If a scaled window is moved throughout the record time, it is equivalent to STFT analysis at that scale.**
- **Corrected MFT (A novel Technique)**
  - **Scaling of the signal through DWT using 'Daubechies 8' wavelet**
  - **Applying the Hanning window in the scaled signal ('Details 2')**

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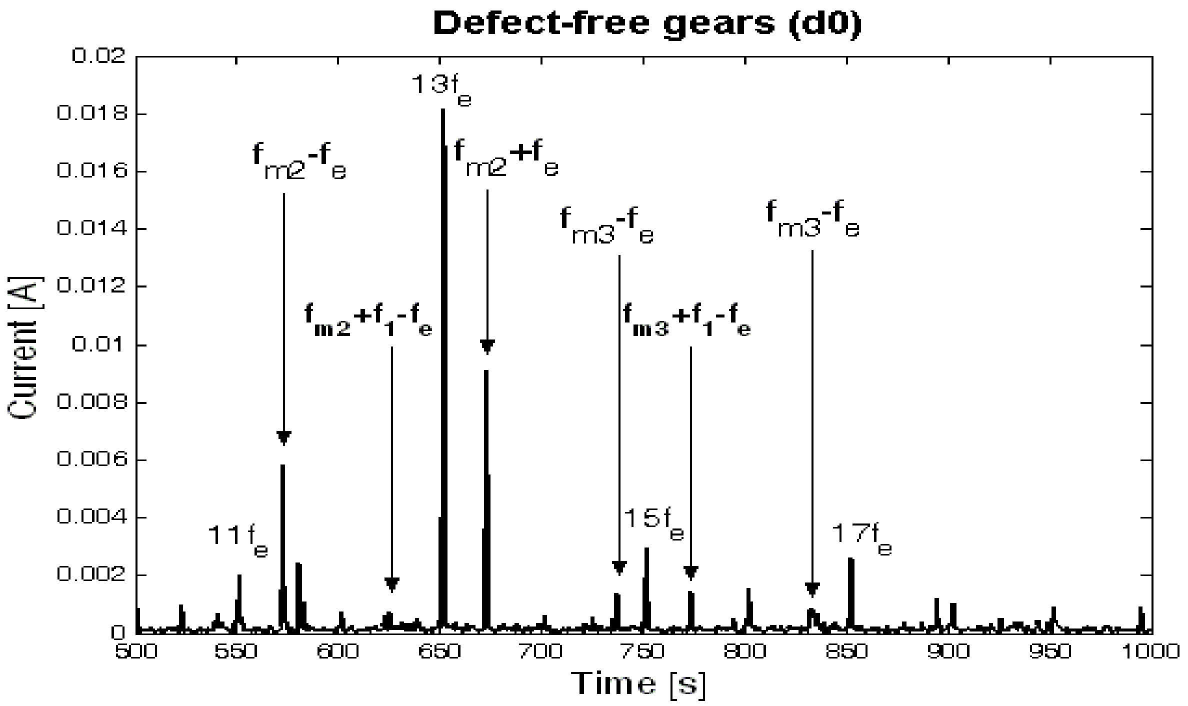
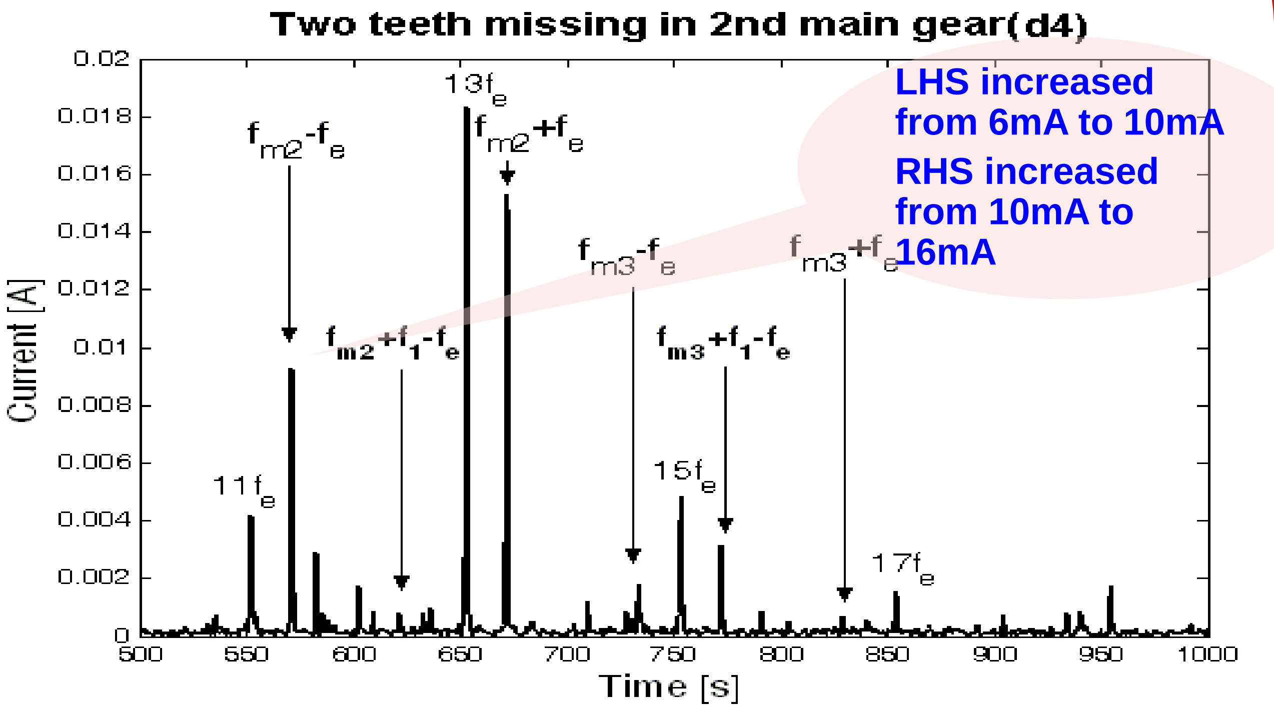
Results : MFT (constant window) of current signals

Current Signal

Normal Gear



Defective Gear



- Gear Mesh Frequencies could be detected in current signals
- Sidebands across GMF could also also be detected
- This technique can trace even 1 mA of current
- By monitoring the amplitude, failure can be detected

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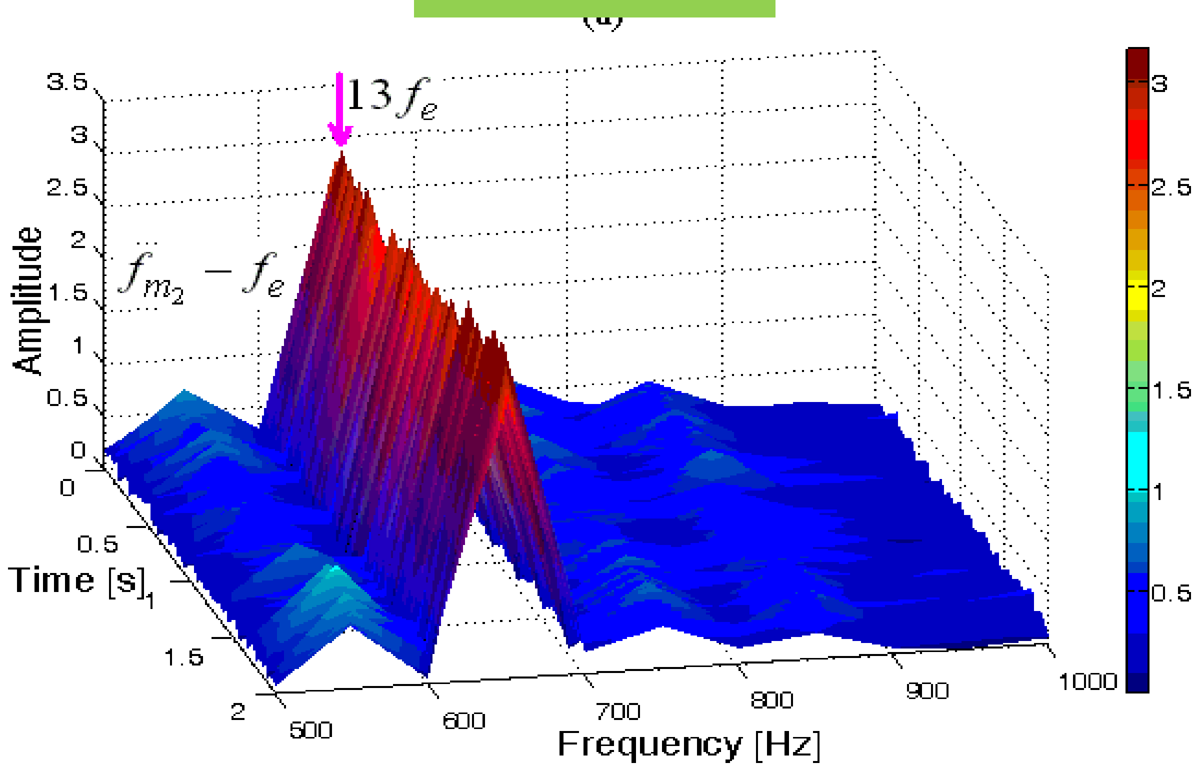
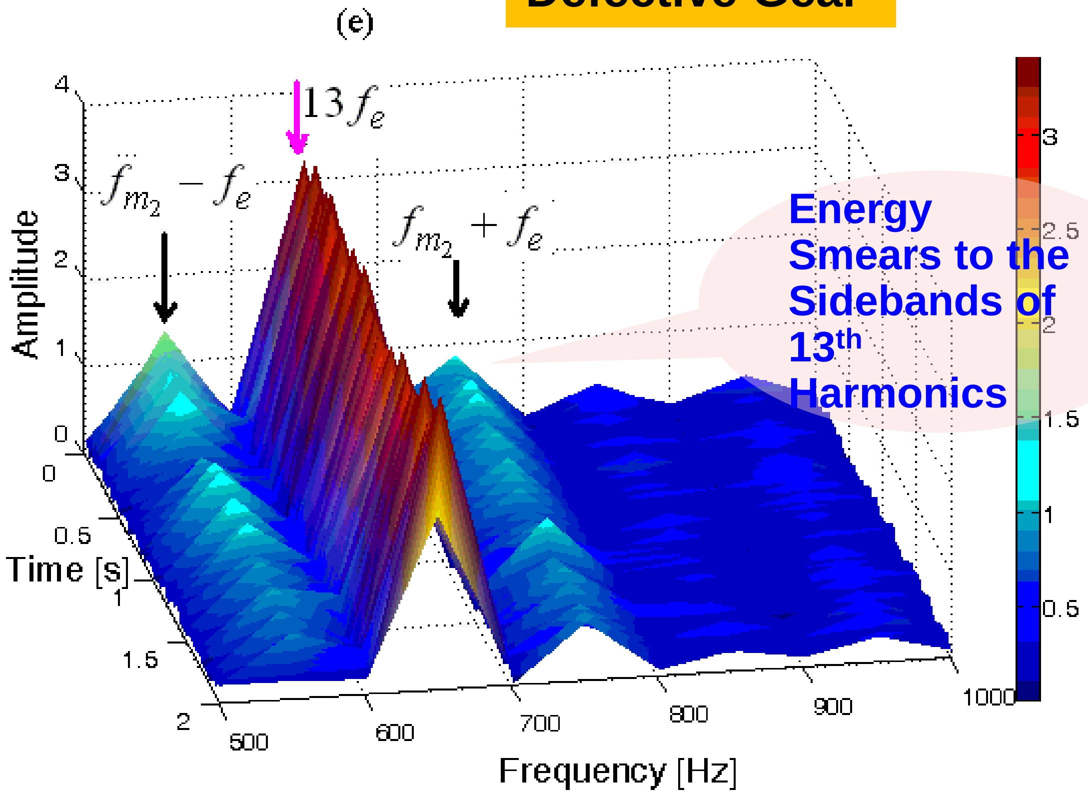
Results : MFT (moving window) of Current Signal

Current Signal

Normal Gear



Defective Gear



Energy Smears to the Sidebands of 13th Harmonics

- Defect-free case:13th harmonics of line frequency is predominant
- Energy increase in the sidebands can be monitored to detect failures

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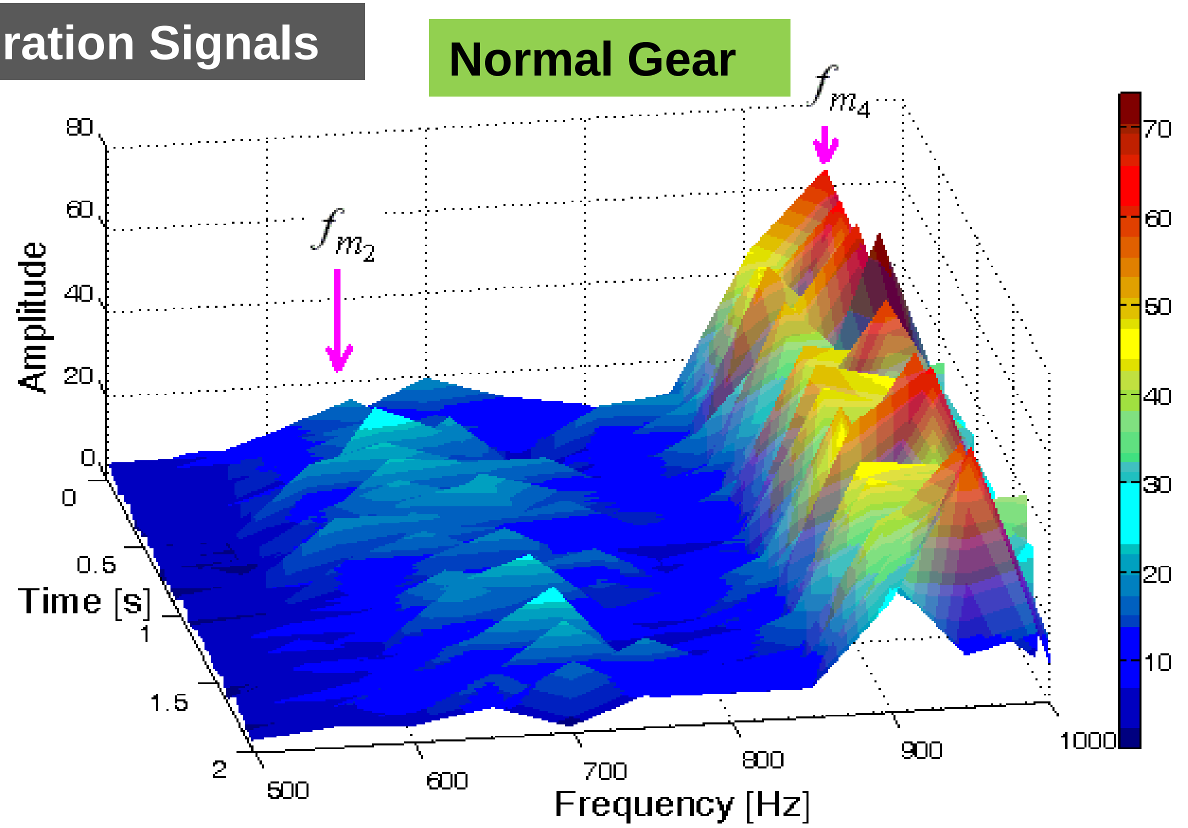
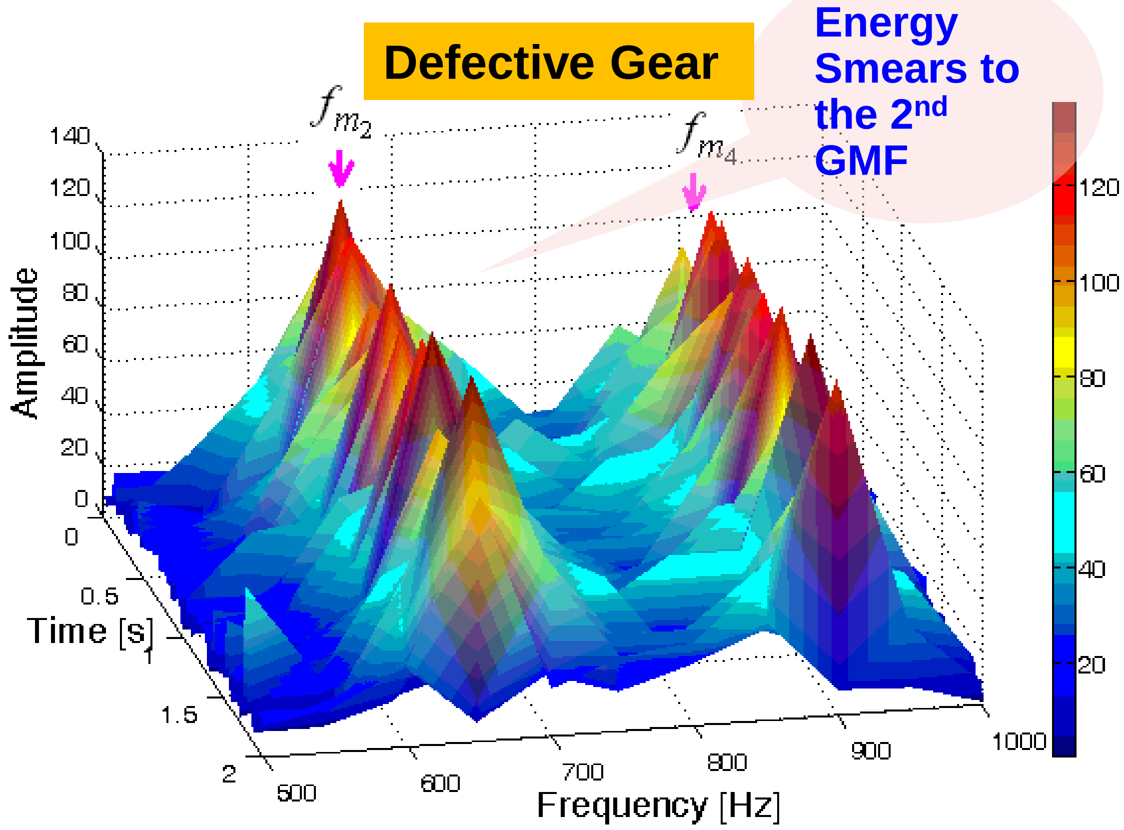
Comparison of the MFT of vibration and current signals

Vibration Signals





- Defect-free case: 4th GMF is predominant
- With increase in defects, 2nd GMF gains energy
- The same phenomenon has been observed in simple FFT analysis

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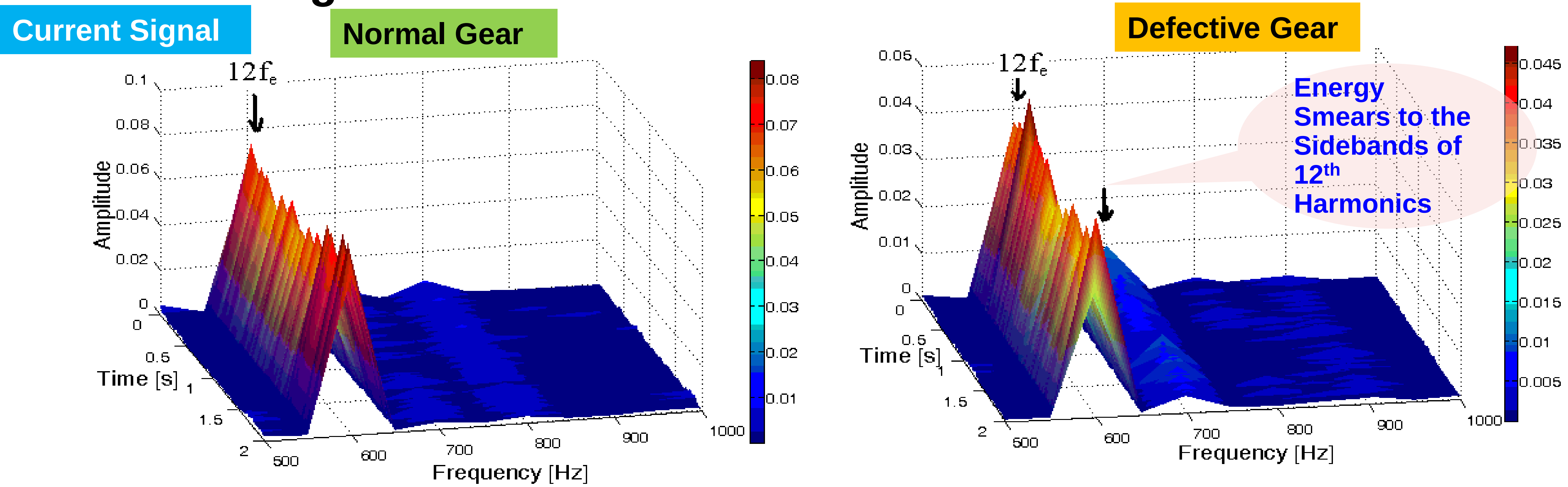
Results : MFT (moving window) of Frequency demodulated current signals



- Defect-free case: 12th harmonics of line frequency is predominant
- With defects, energy smears to the shaft frequency sidebands of GMF

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Conclusions

- Various Analysis techniques have been discussed so as to detect mechanical failures
- Corrected MFT is proficient in analyzing the signal.
- Even a high frequencies of Gear Mesh Frequencies could be detected using Motor Current Signature Analysis
- The developed monitoring scheme can be extended or modified to analyze any type of gearbox
- The following additional cases have been examined and same results are found (But out of scope of this presentation due to time constraints)
    - Noise signal and speed signals
    - At various loads
    - With various transients

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Thank You

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