Review of Techniques for Bearings & Gearbox Diagnostics

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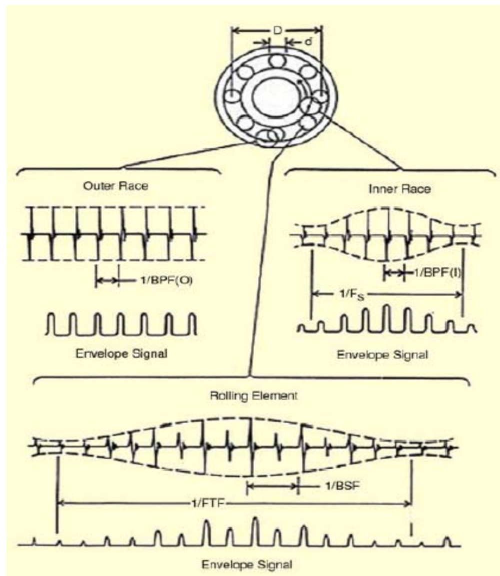
Jacksonville FL

Rolling Element Bearing Faults

Rolling Element Bearing Faults

- Ball damage
- Inner race defect
- Outer race defect
- Cage damage



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Rolling Element Bearing Faults

ball passing frequency outer race $BPFO = \frac{nf_r}{2}\left\{1 - \frac{d}{D}\cos\phi\right\}$

ball passing frequency inner race $BPFI = \frac{nf_r}{2}\left\{1 + \frac{d}{D}\cos\phi\right\}$

fundamental train frequency $FTF = \frac{f_r}{2}\left\{1 - \frac{d}{D}\cos\phi\right\}$

Ball spin frequency $BSF = \frac{D}{2d}\left\{1 - \left(\frac{d}{D}\cos\phi\right)^2\right\}$

D = pitch dia; d = ball dia; ϕ = contact angle;
n = no. of balls

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Assumptions Made in Bearing Fault Frequencies Equations

1. All balls/rollers are equal in diameter
2. There in pure rolling contact between balls, inner race and outer race.
3. There is no slipping between the shaft and the bearing
4. Outer race is stationary and inner race rotates

In practice there is always some sliding and slippage specially when a bearing is under load and after some wear

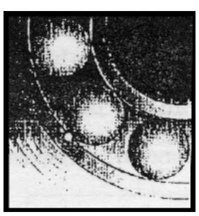
Approximate formulas:

BPFI = 0.55-0.6 x No. of balls x RPM

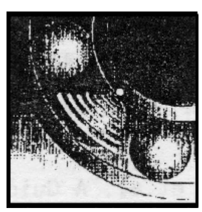
BPFO=0.45 x No. of balls x RPM

BSF = 3.5 x RPM

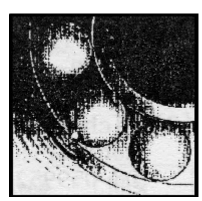
Bearing Defects



BPFO



BPFI



BSF

Time Domain Impact Response

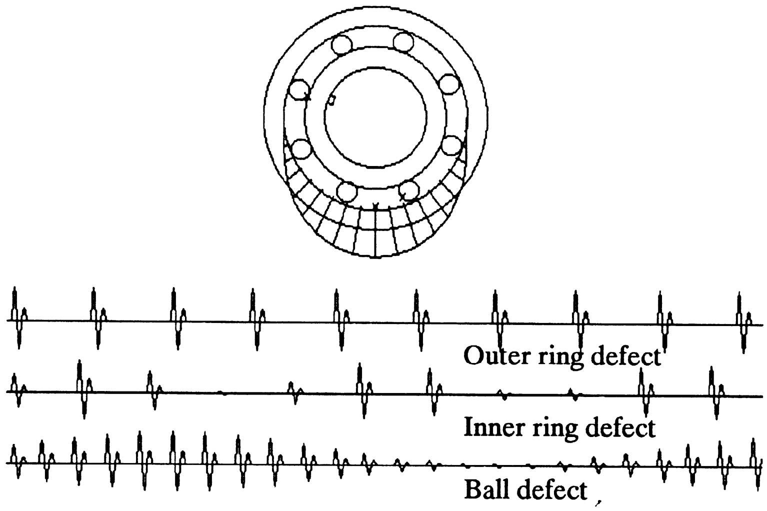
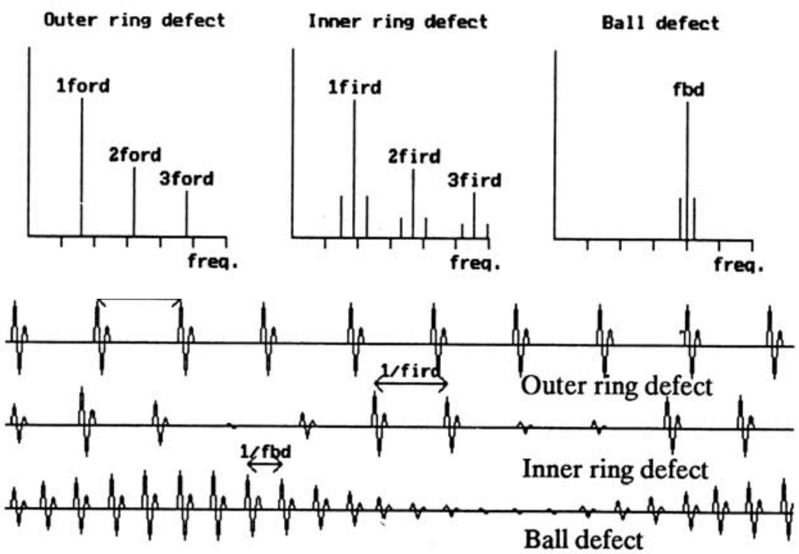


Illustration of Sidebands



How do we analyze vibration signature of bearing faults? & Issues

- Observe the time waveform and the spectrum to see differences between the good and bad bearing data
- Compare the observed frequencies with the calculated frequencies. Are the peaks present ?
- Signals are often masked by large amplitude periodic components
- Direct Spectral analysis may not give sufficient information
- Bearing faults create a series of impacts witch are amplified by resonances: bearing, sensors, structure etc
- This creates envelopes of specific faults at high frequencies
- Fault signals are not periodic; appear more like random
- Some cases can be treated as cyclostationary
- New techniques are still being developed

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Techniques Currently used in Industrial Products

- Time Waveform Analysis
- Frequency Spectral Analysis
- High Frequency Detection (HFD)
- Stress Wave Analysis or Spike Energy
- PeakView ®
- Enveloping

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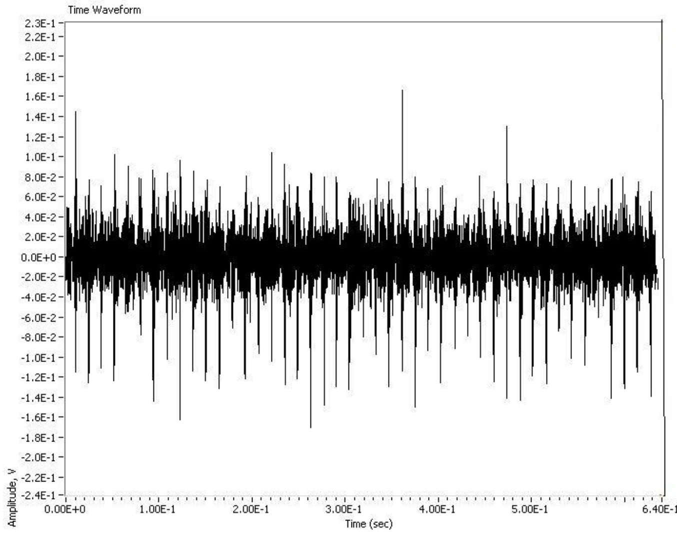
Typical Bearing Outer race Fault Waveform



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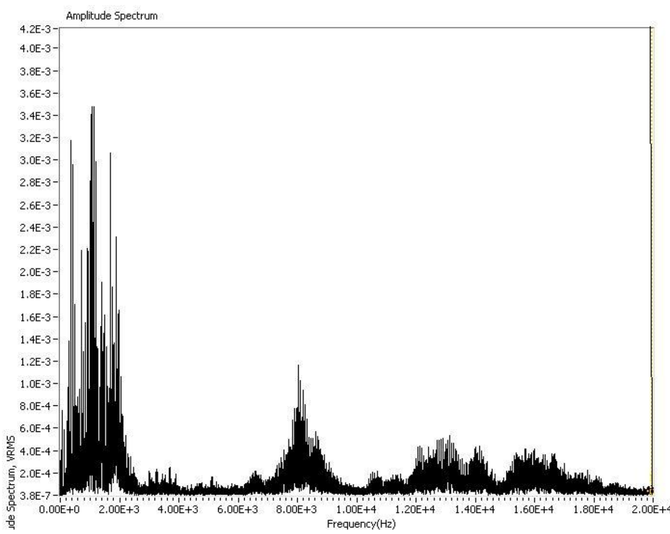
Typical Bearing Outer race Fault Spectra



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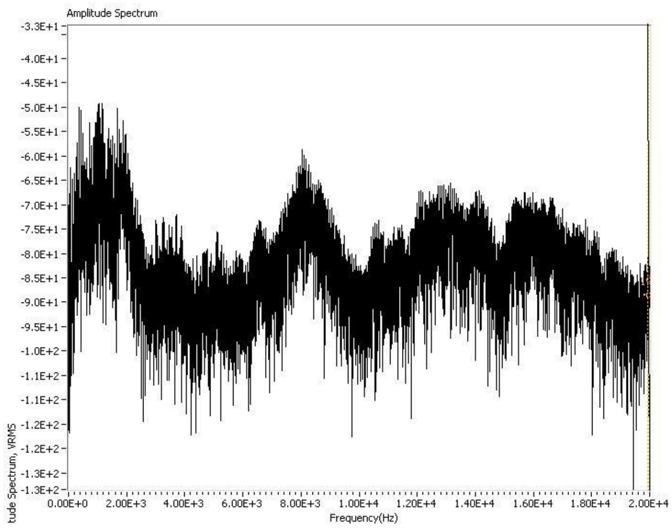
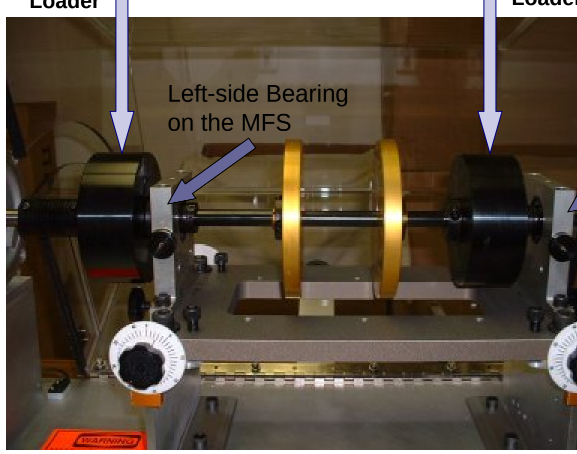
Typical Bearing Outer race Fault Spectra



Bearing Fault

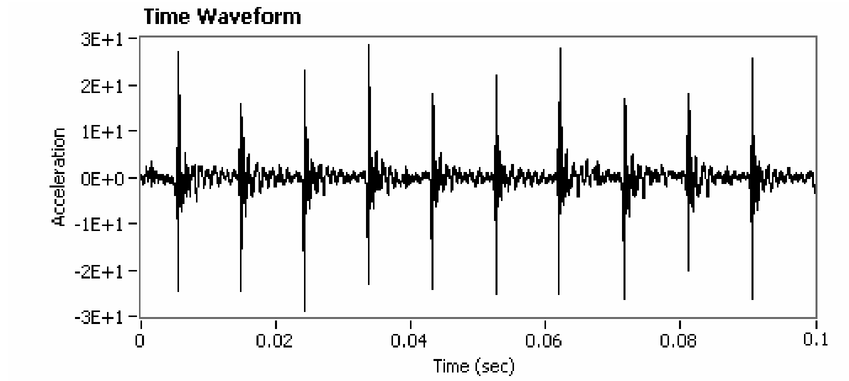
Bearing Loader

Bearing Loader



Right-side Bearing on the MFS

Bearing Outer Race Faults



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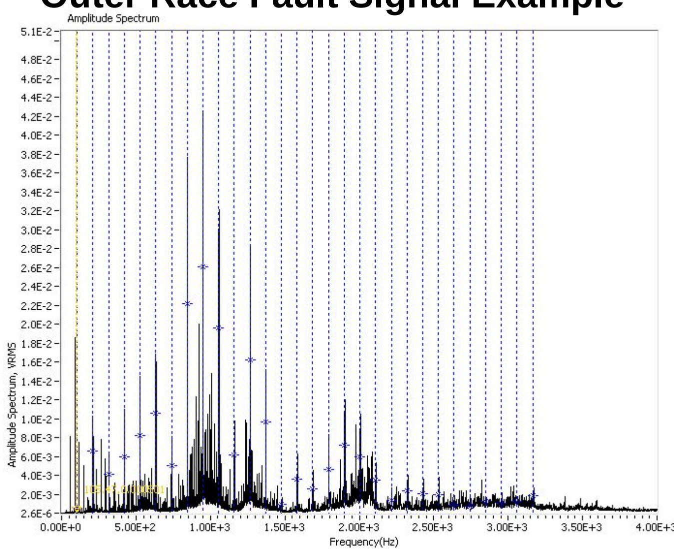
Outer Race Fault Signal Example



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The harmonics of BPFO show up clearly

MB ER-10K bearing parameters:
Number of rolling element: 8
Rolling element diameter: 0.3125 Inches
Pitch diameter: 1.319 inch
Contact angle: 0 degree

$$BPFO = \frac{Nb}{2} * (1 - \frac{Bd}{Pd} * \cos\theta)$$

Bearing Faults for MB ER-10K bearing at the Running Speed of 2,004 RPM

Notation	Fault Frequency Multiplier	Fault Frequency (Hz)	Harmonics of the Running Speed	Harmonic Frequencies (Hz)	Delta Frequencies (Hz)	Resolution to Detect the Fault Frequencies = Delta Frequencies/4 (Hz)
BPFI	4.9480	165.3176	5	167.0570	1.7394	0.4349
BFPO	3.0520	101.9704	3	100.2340	1.7364	0.4341
BSF	1.9920	66.5547	2	66.8230	0.2683	0.0671

RPM Harmonics

1	2	3	4	5	6	7	8
33.411	66.823	100.234	133.646	167.057	200.469	233.880	267.291
1.674E-5	1.966E-5	1.014E-5	4.219E-5	1.309E-4	7.179E-5	9.206E-5	7.807E-5

Spectral Resolution for 5,000 Hz Maximum Frequency Setting

Spectral Lines	Resolution, Hz	Resolution, RPM
100	50.0000	3,000.0000
200	25.0000	1,500.0000
400	12.5000	750.0000
800	6.2500	375.0000
1,600	3.1250	187.5000
3,200	1.5625	93.7500
6,400	0.7813	46.8750
12,800	0.3906	23.4375
25,600	0.1953	11.7188
51,200	0.0977	5.8594
102,400	0.0488	2.9297

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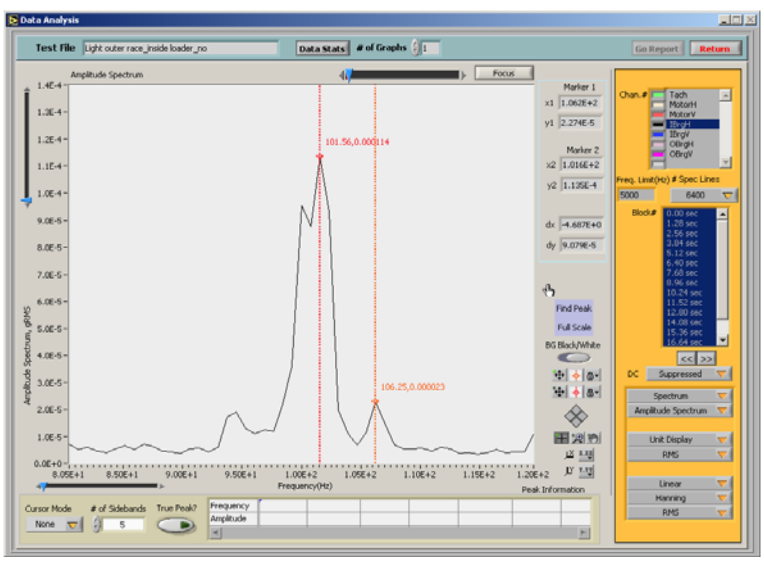
Resolution: 6400 FFT Lines using a Hanning Window



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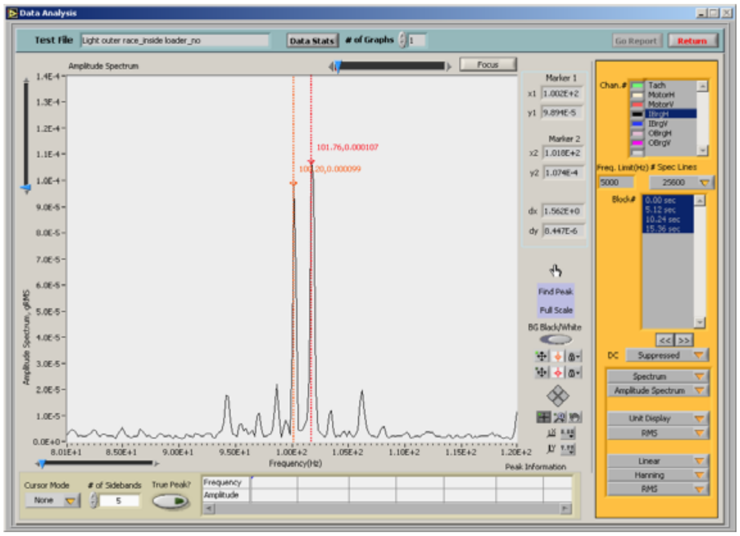
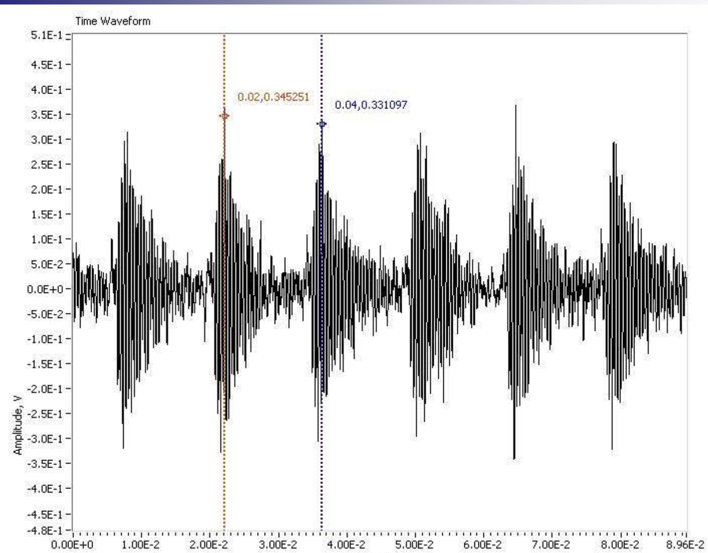
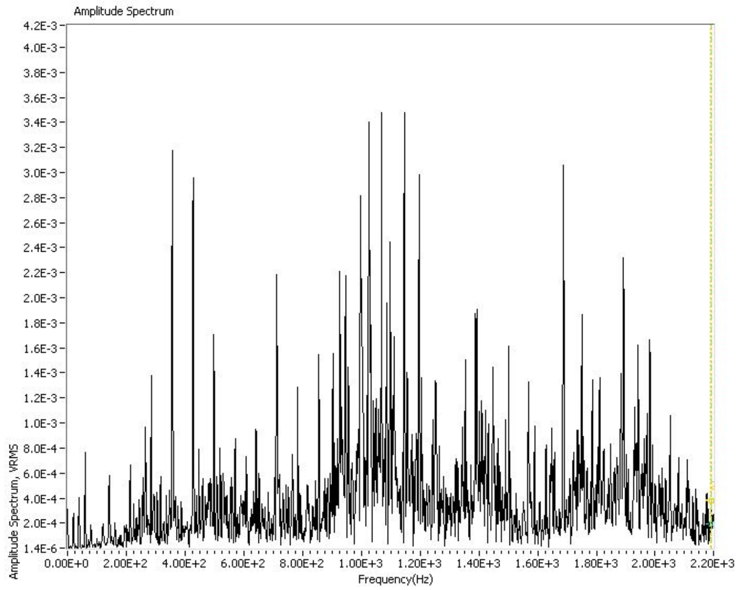
Resolution: 25600 FFT Lines using a Hanning Window



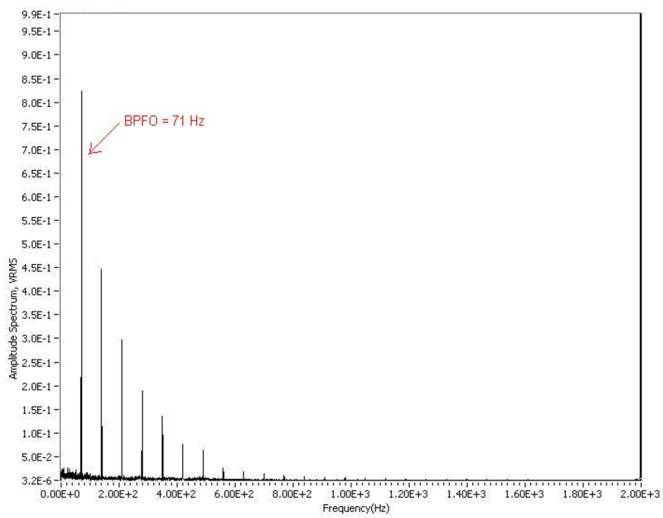


Acceleration signals acquired from an outer race faulted bearing
BPFO which is roughly 71 Hz (=1/0.014)



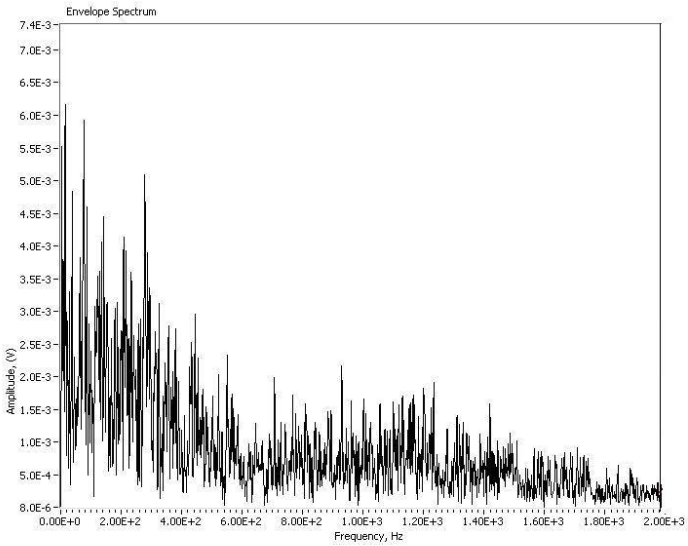
Acceleration signals acquired from an outer race faulted bearing BPFO which is roughly 71 Hz (=1/0.014)

Envelope Spectra



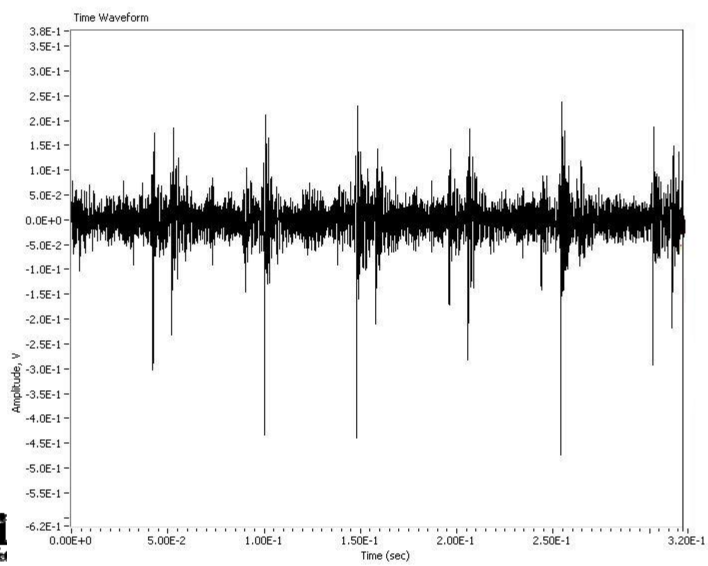
Envelope spectrum of the faulted bearing (outer race) showing the BPFO demodulated in the frequency band of 2000Hz-4000Hz

Effect of demodulation band

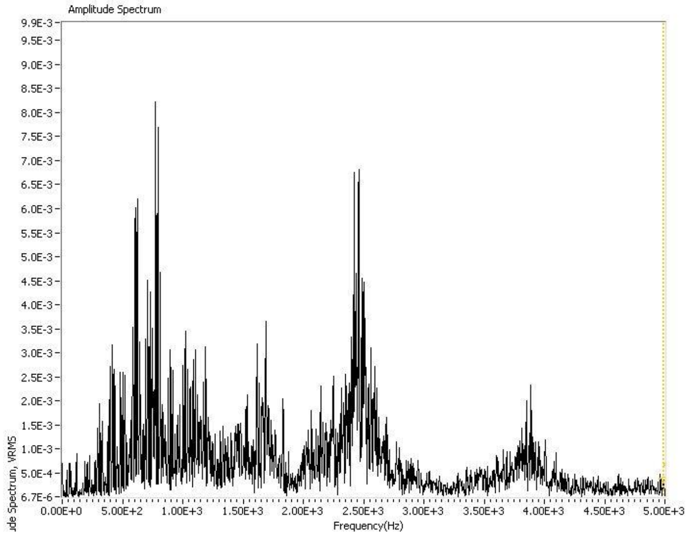


Envelope spectrum of the faulted bearing (outer race) not showing the BPFO demodulated in 10k-12k Hz band

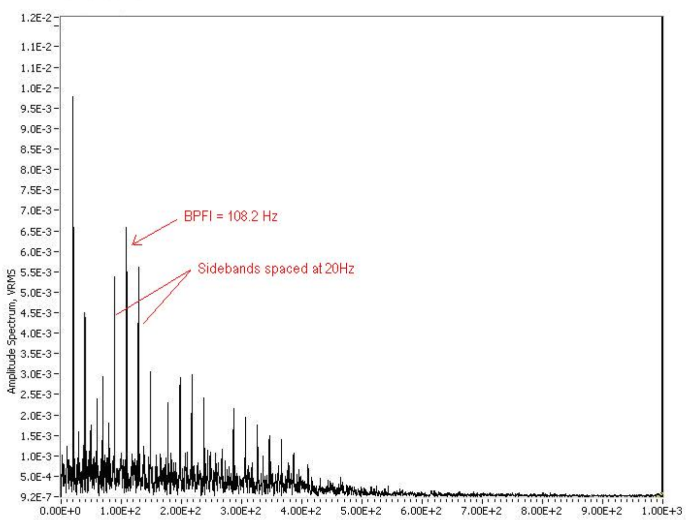
Inner race Fault Time Waveform



Inner Race Fault Spectra

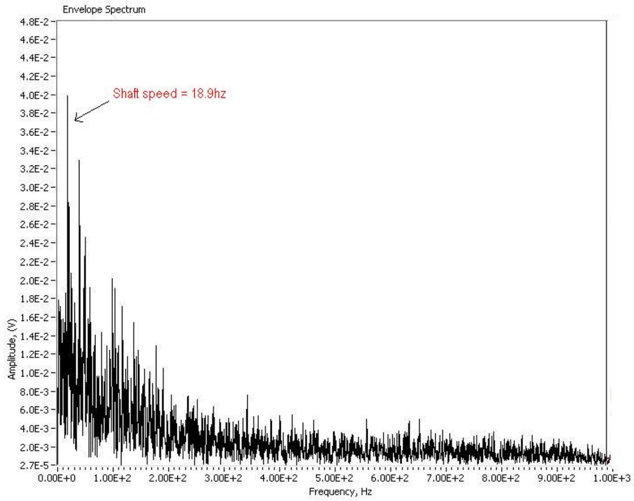


Envelope Spectrum



Envelope spectrum of the inner race faulted bearing with a shaft speed of 20 Hz showing the BPFI and sidebands with a 750 psi load

Effect of load



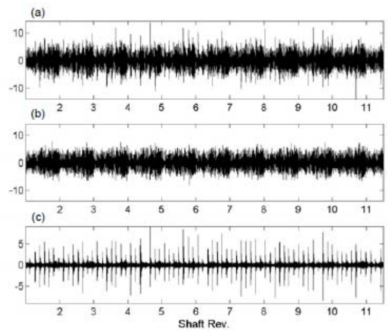
Envelope spectrum of the inner race faulted bearing not showing the BPFI under no load

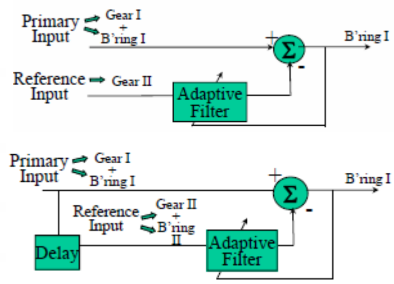
New Techniques under Research

- Adaptive Noise Cancellation (ANC)
- Self-adaptive Noise Cancellation (SANC)
- Spectral Kurtosis
- Discrete Random Separation
- Cyclostationary Signal Analysis
- Julian
- Hilbert-Huang Transform
- Entropy

Adaptive Noise Cancellation (ANC)

- Removes the random components from the periodic components
- Requires reference input along with primary input
- SANC uses the delayed primary signal as reference signal
- It uses the fact that bearing signals has a short correlation length





Ref: Prof. Bob Randall

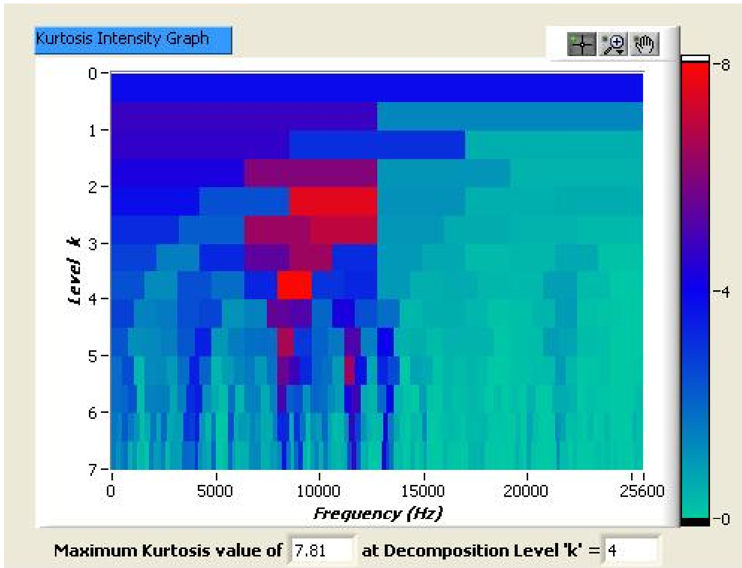
Fault bearing signal with gear signal (b) Gear signal –discrete components (c) Bearing components- random components

Spectral Kurtosis

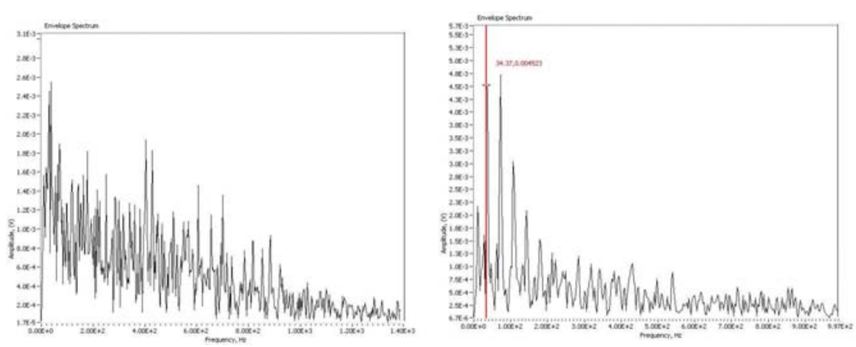
- Calculates Kurtosis for each frequency line
- Identifies the impulsiveness in the data
- Uses short time Fourier transform
- Determines optimum band for demodulation

$$kurtosis\,(y) = \frac{mean\,(y^2)}{(mean\,(y))^2} - 2$$

y = autospectrum value (ie amplitude squared)



Spectral Kurtosis showing the maximum excited frequency bands (fc=8800hz, bw=1600hz) using outer race faulted bearing



(a) Envelope spectrum showing the BPFO(34.4Hz) in freq. range 8000-9400 hz
(b) Envelope spectrum showing harmonics of BPFO much clearly in 4000-5000hz band

Gearbox Diagnostics

Techniques for Gearbox Vibration Analysis

- Time Waveform Analysis
- Spectral Analysis
- Order Analysis
- Time synchronous averaging
- Cepstrum Analysis
- Amplitude and Phase Demodulation
- Transmission Error Analysis

Gear Diagnostic Parameters (Vibration Based) Page 1 of 2

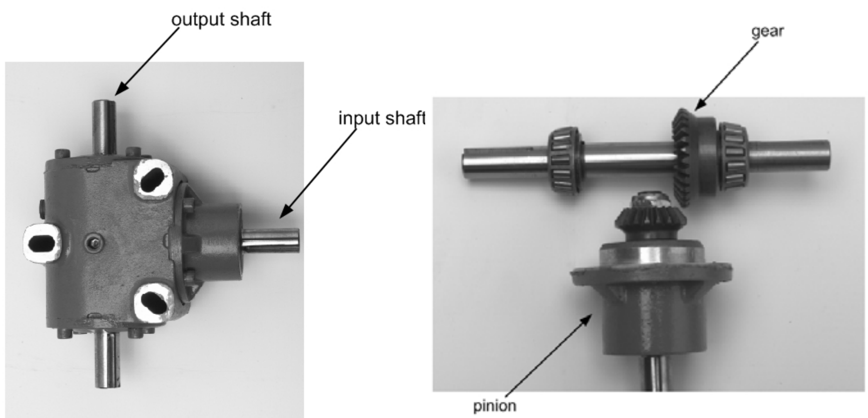
MFPT

Gear Diagnostic Parameters (Vibration Based)

Parameter	Reference
RMS	Root Mean Square of the signal
Kurtosis	4th Statistical Moment of the signal normalized by the square of the variance of the signal.
Delta RMS	Change in the Root Mean Square of the signal
Crest Factor	Swansson, N.S. Application of Vibration Signal Analysis Techniques to Signal Monitoring. Conference on Friction and Wear in Engineering 1980. Institution of Engineers, Australia, Barton, Australia, 1980, pp 262-267.
Sideband Level Factor	Favaloro, S.C. A Preliminary Evaluation of Some Gear Diagnostics Using Vibration Analysis. ARL-AERO-RPOP-TM-427, Aeronautical Research Laboratory, Department of Defence, Melbourne, Australia, 1985.
Energy Ratio	Swansson, N.S. Application of Vibration Signal Analysis Techniques to Signal Monitoring. Conference on Friction and Wear in Engineering 1980. Institution of Engineers, Australia, Barton, Australia, 1980, pp 262-267.
FM0	Stewart, R.M. Some Useful Data Analysis Techniques for Gearbox Diagnostics. Machine Health Monitoring Group, Institute of Sound and Vibration Research, University of Southampton, Report MHM/R/10/77, July 1977.
FM2	Stewart, R.M. Some Useful Data Analysis Techniques for Gearbox Diagnostics. Machine Health Monitoring Group, Institute of Sound and Vibration Research, University of Southampton, Report MHM/R/10/77, July 1977.
FM4	Stewart, R.M. Some Useful Data Analysis Techniques for Gearbox Diagnostics. Machine Health Monitoring Group, Institute of Sound and Vibration Research, University of Southampton, Report MHM/R/10/77, July 1977.
M6A	Martin, H.R. Statistical Moment Analysis As a Means of Surface Damage Detection. Proceedings of the 7th International Modal Analysis Conference, Society for Experimental Mechanics, Schenectady, NY, 1989, pp. 1016-1021.
M8A	Martin, H.R. Statistical Moment Analysis As a Means of Surface Damage Detection. Proceedings of the 7th International Modal Analysis Conference, Society for Experimental Mechanics, Schenectady, NY, 1989, pp. 1016-1021.
NA4	Zakrajsek, J.J., Townsend, D.P., Decker, H.J. An Analysis of Gear Fault Detection Methods as Applied to Pitting Fatigue Failure Data. NASA Lewis Research Center/U.S. Army Aviation Systems Command. 47th Mechanical Failure Prevention Group, NASA TM 105950, AVSCOM TR 92-C-035, April 1993.
NA4*	Decker, H.J., Handschuh, R.F., Zakrajsek, J.J. An Enhancement to the NA4 Gear Vibration Diagnostic Parameter. U.S. Army Research Laboratory/NASA Glenn Research Center. 18th Annual Meeting of the Vibration Institute, NASA TM 106553, ARL-TR-389, June 1994.
NB4	Zakrajsek, J.J., Handschuh, R.F., Decker, H.J. Application of Fault Detection Techniques to Spiral Bevel Gear Fatigue Data. NASA Lewis Research Center/U.S. Army Research Laboratory 48th Mechanical Failures Prevention Group, Wakefield, Mass. April 1994. NASA TM 106467, ARL-TR-345
NB4*	Application of difference between NA4 and NA4* to NB4. No paper published.
NP4	Polyshchuk, V.V., Choy, F.K., Braun, M.J. Gear Fault Detection with Time-Frequency based Parameter NP4. Proceedings from the 8th International Symposium on Transport Phenomena and Dynamics of Rotating Machinery (ISROMAC-8), Honolulu, Hawaii,

http://mfpt.org/Archive%20Old%20Pages/mfpt_geardiagnosticparam.html 1/28/2010

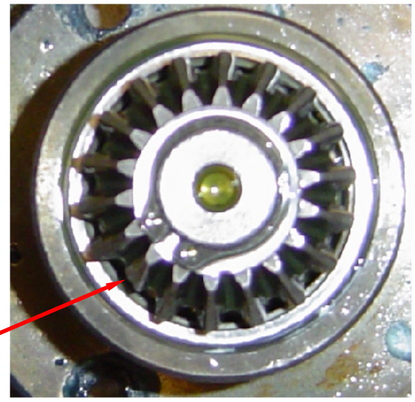
Gearbox Vibration



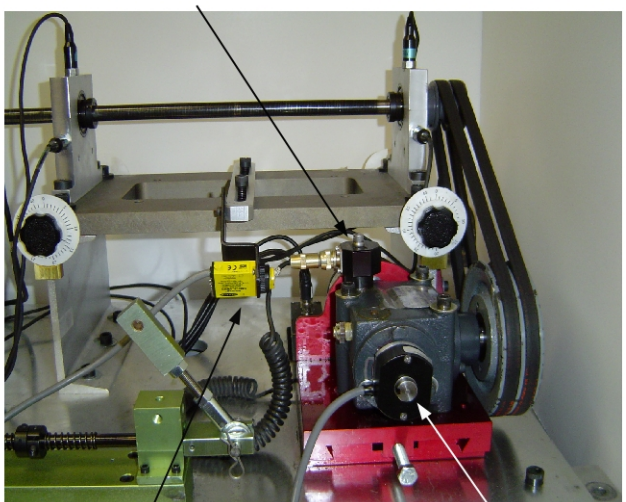
Transmission ratio: 1.5:1, (27 and 18 teeth)

Gearbox Vibration

Missing of tooth



Gearbox Vibration



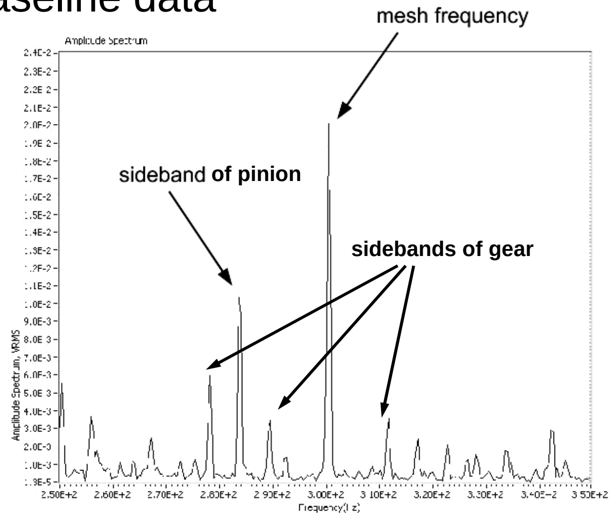
tri-axial accelerometer

tachometer

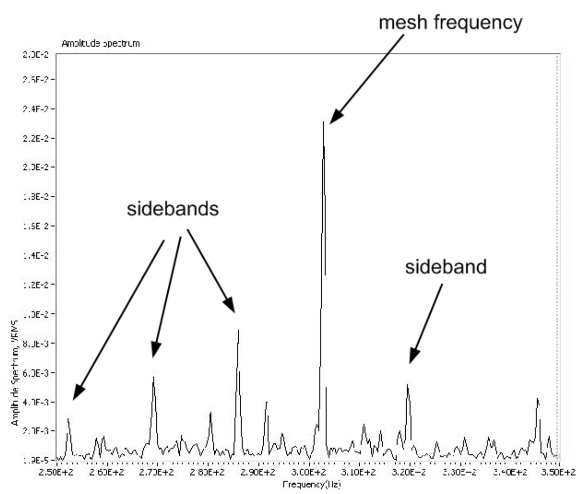
encoder

Gearbox Vibration

Baseline data

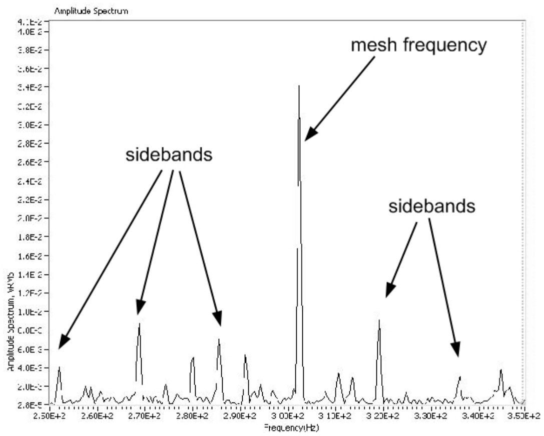


Spectrum of Fault Level 1 Data

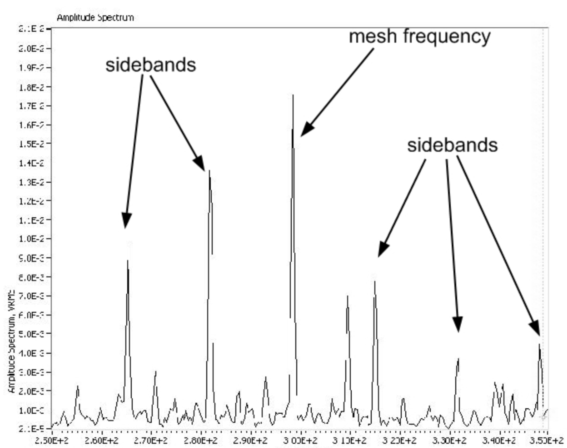


Compared with baseline, more pinion sidebands emerge

Spectrum of Fault Level 2 Data

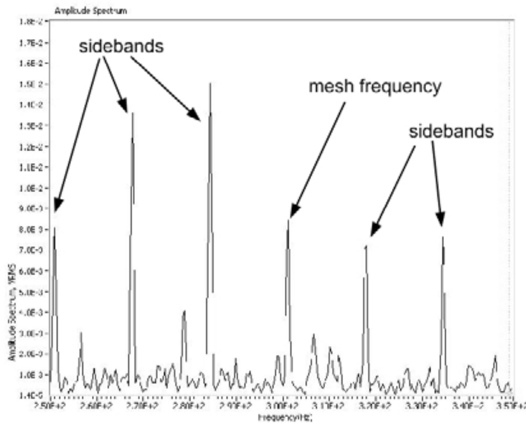


Spectrum of Fault Level 3 Data



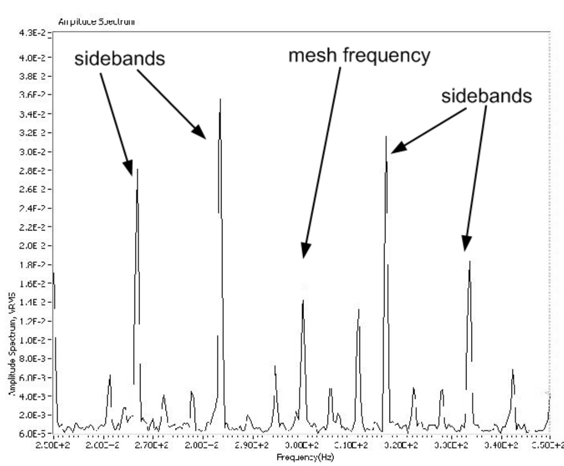
Compared with baseline, the amplitudes of pinion sidebands Increase significantly.

Spectrum of Fault Level 4 Data



The amplitudes of pinion sidebands continually Increase.

Spectrum of Fault Level 5 Data

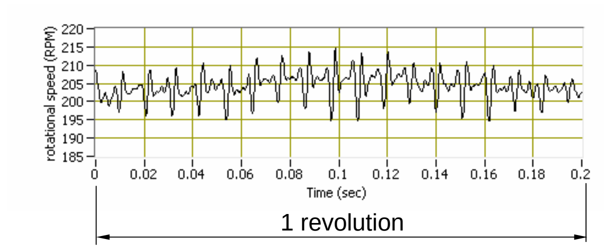


The amplitudes of pinion sidebands exceed that of the mesh frequency
For the missing of a tooth.

Gear vibration – order analysis

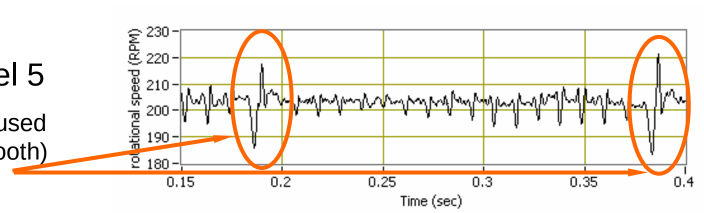
Speed variation captured using encoder

Intact gear
(small spikes are caused by gear meshing)



Fault level 5

(impacts caused by missed tooth)



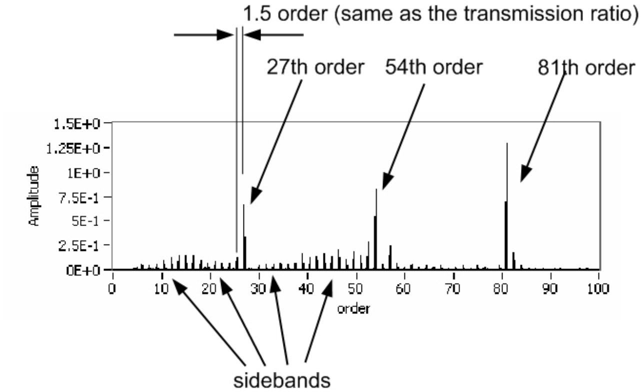
Gear vibration – order analysis

Speed Variation Order Spectrum - baseline

The number of teeth on gearbox output shaft is 27. The 27th, 54th and 81th orders have high amplitude. They correspond to the mesh frequency and its 2nd and 3rd harmonics.

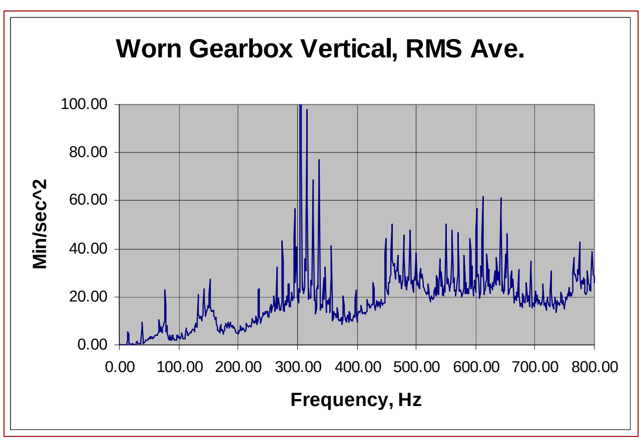
Gear vibration – order analysis

Speed Variation Order Spectrum – fault level 5

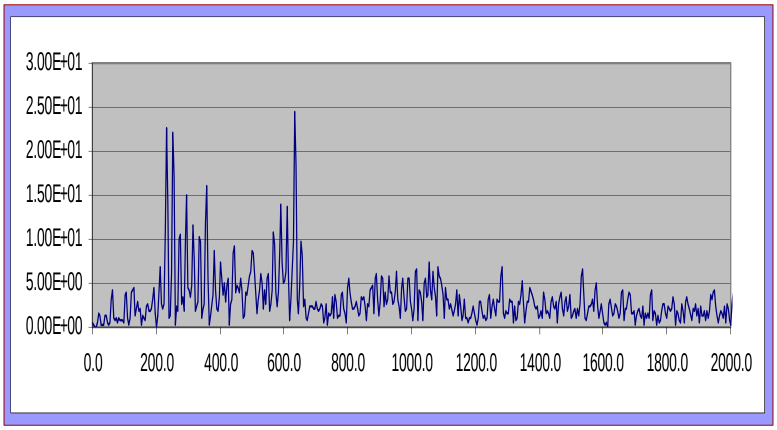


Pinion sidebands emerge clearly for the missing of a tooth

Time Synchronous Averaging



Time Synchronous Averaging



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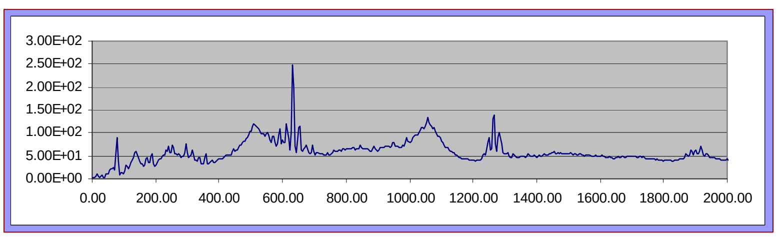
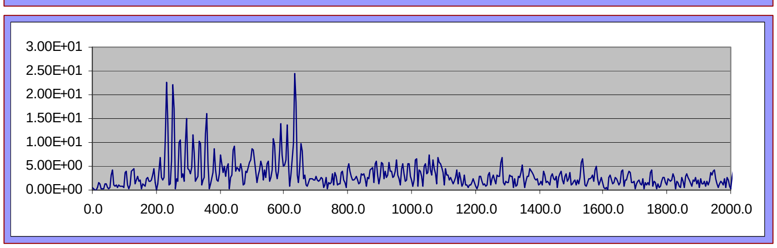
Worn Gearbox data comparison, two Types of Averaging





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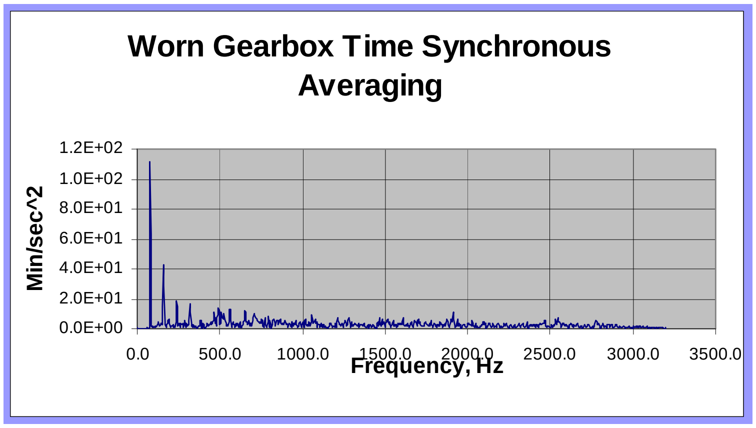
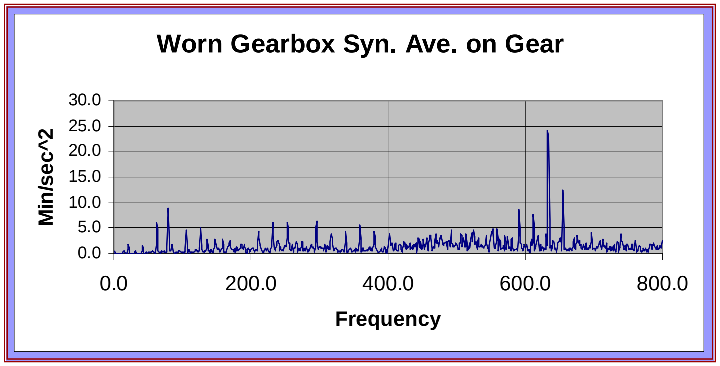
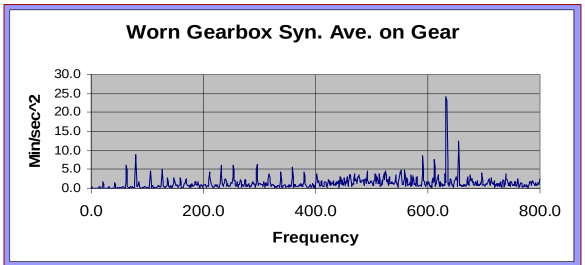
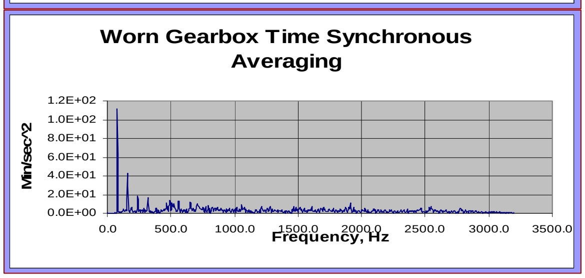

Worn Gearbox Time Synchronous Averaging
Min/sec^2
1.2E+02
1.0E+02
8.0E+01
6.0E+01
4.0E+01
2.0E+01
0.0E+00
0.0
500.0
1000.0
1500.0
2000.0
2500.0
3000.0
3500.0
Frequency, Hz


Worn Gearbox Syn. Ave. on Gear
Min/sec^2
30.0
25.0
20.0
15.0
10.0
5.0
0.0
0.0
200.0
400.0
600.0
800.0
Frequency

Worn Gearbox data comparison, TSA at Two Shafts





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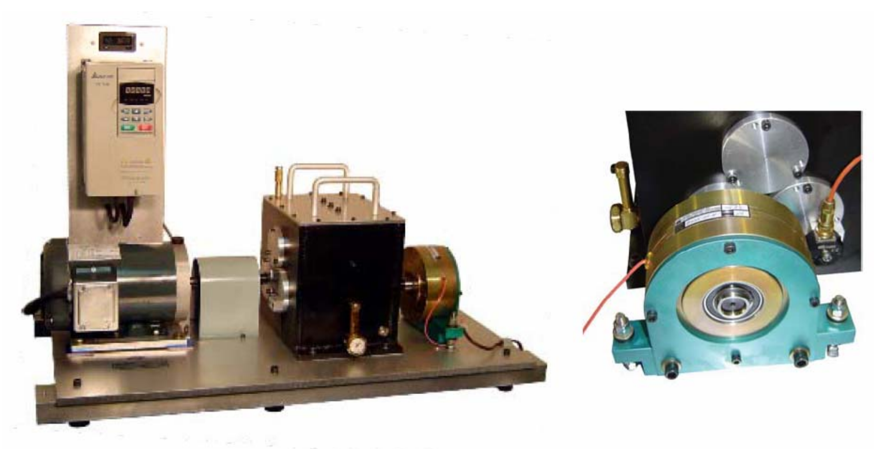

Figure 1. Gearbox dynamics simulator and the magnetic brake.

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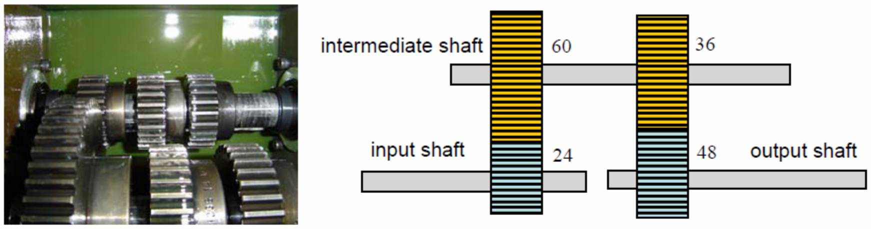

(a) (b)

Figure 2. Two-stage parallel gear transmission.

(a) (b) (c)

Figure 3. Faulted gears. (a) Small chipped tooth, (b) large chipped tooth, (c) missing tooth.

Speed = 59.37 Hz

$$f_{m1} = 24 \times f_i \,,$$

$$f_{m2} = f_i \times \frac{24}{60} \times 36 \,,$$

f_{m1} and f_{m2} are roughly 1425 Hz and 854 Hz,

Side bands = 59.37, 23.7, 17.8 Hz

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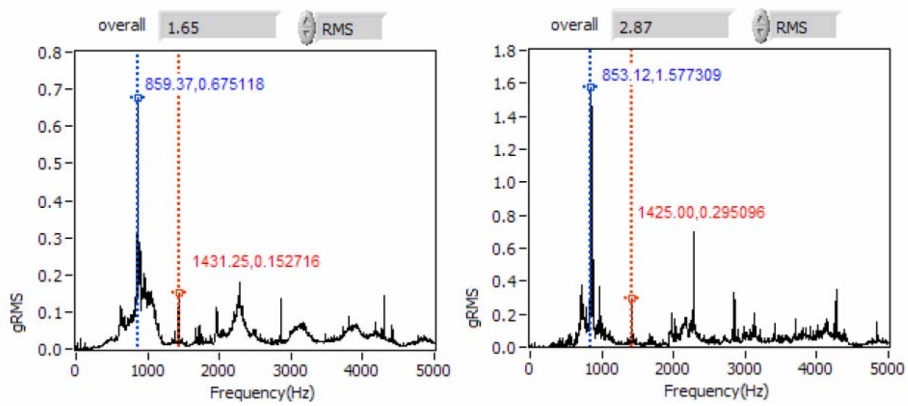
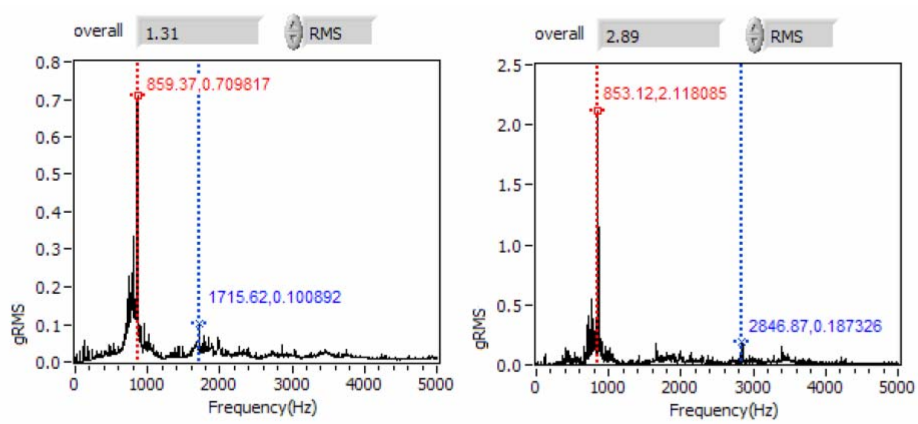
Baseline Data



(a) (b)

Figure 5. Gearbox acceleration spectra of baseline data. (a) without load, (b) with load.

Chipped Tooth Data



(a) (b)

Figure 6. Gearbox acceleration spectra of Test 6. (a) without load, (b) with load.

Chipped Tooth Data

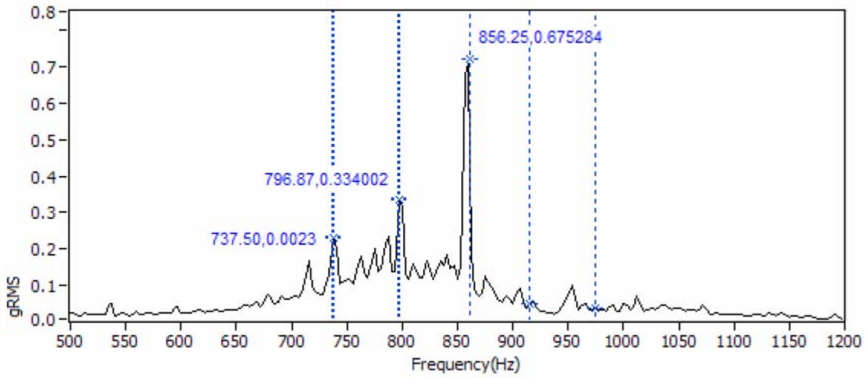
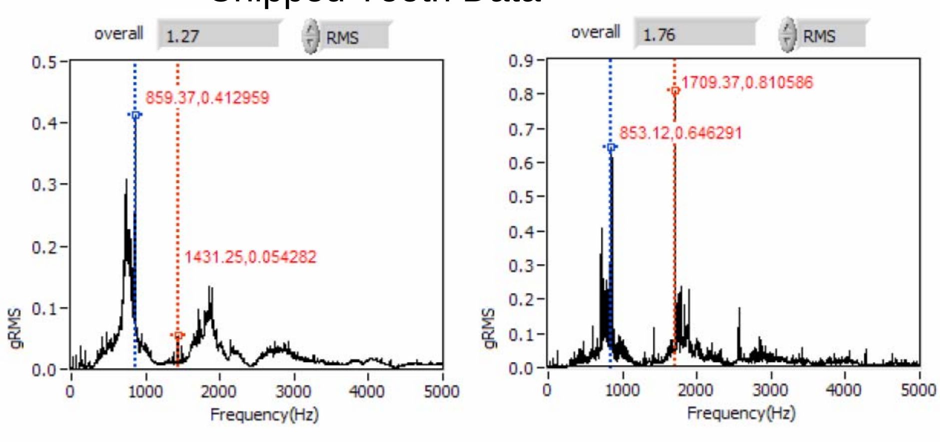


Figure 7. Sideband presented about the second meshing frequency.

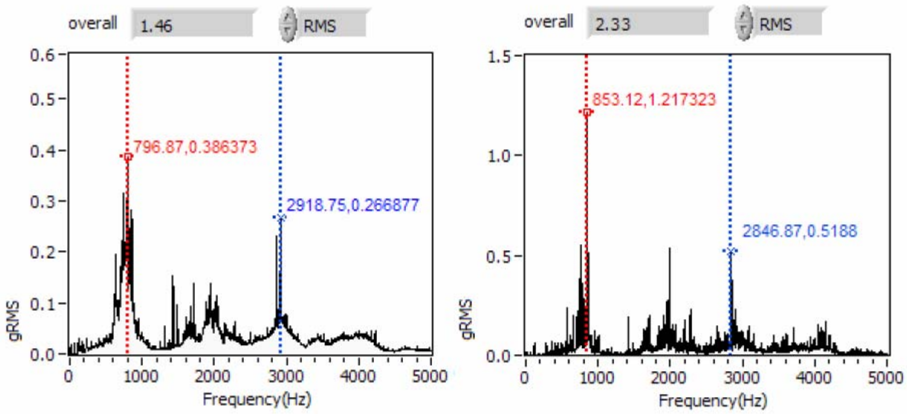
Chipped Tooth Data



(a) (b)

Figure 8. Gearbox acceleration spectra of Test 7. (a) without load, (b) with load.

Missing Tooth Data



(a) (b)

Figure 9. Gearbox acceleration spectra of Test 5. (a) without load, (b) with load.

Missing Tooth Data

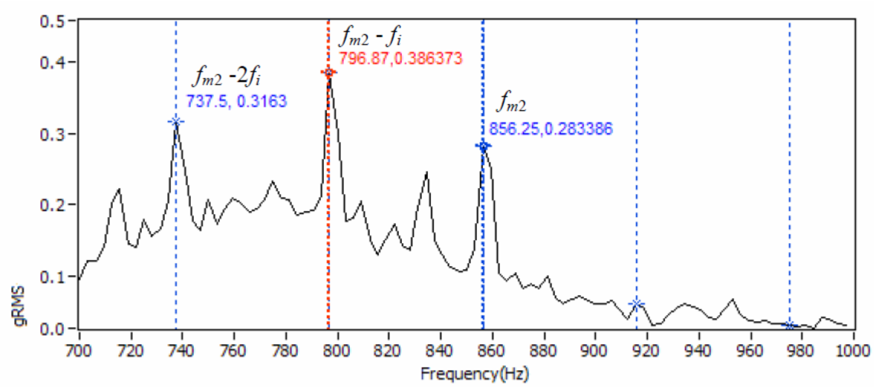


Figure 10. Sidebands about f_{m2}.

Missing Tooth Data

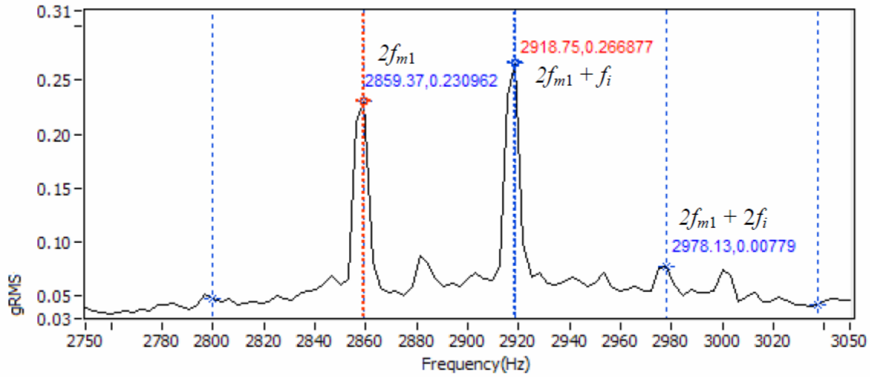


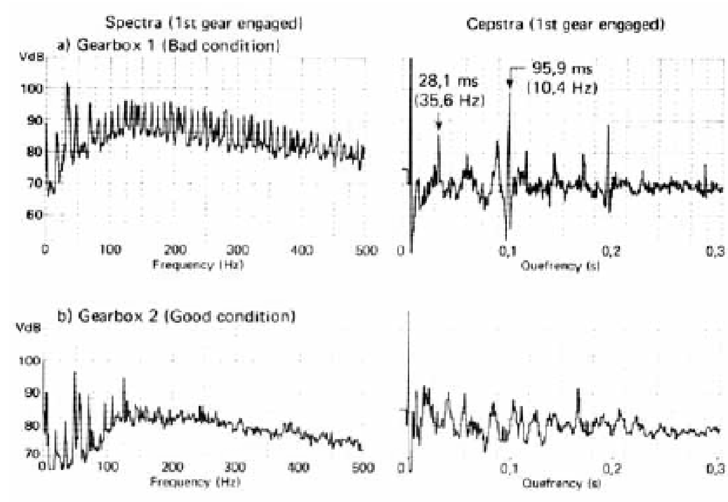
Figure 11. Sidebands about the $2f_{m1}$.

- Cepstrum Analysis
  - Inverse Fourier transform of logarithmic spectrum
  - Useful for detecting changes in sideband families
  - Echo, Transmission path, etc
  - Quefrency, Rahmonic, Gamnitude, Lifter, Saphe

$$C(\tau) = \Im^{-1}\left[\log\left(X(f)\right)\right]$$

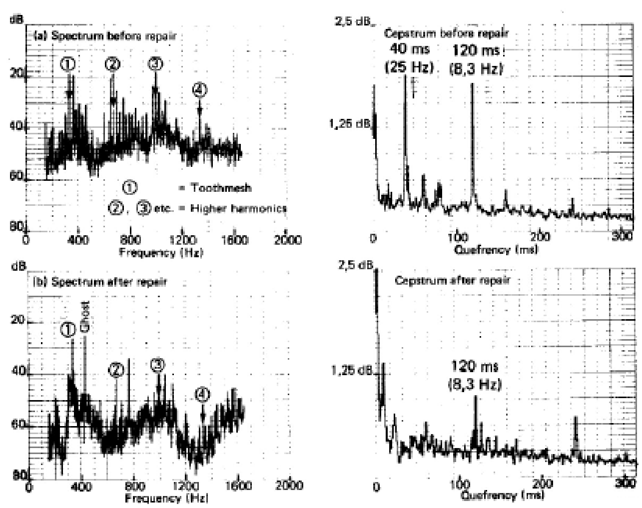
Where X(f) is the Fourier transform of x(t)

Cepstrum Analysis



Ref: Prof. Bob Randall

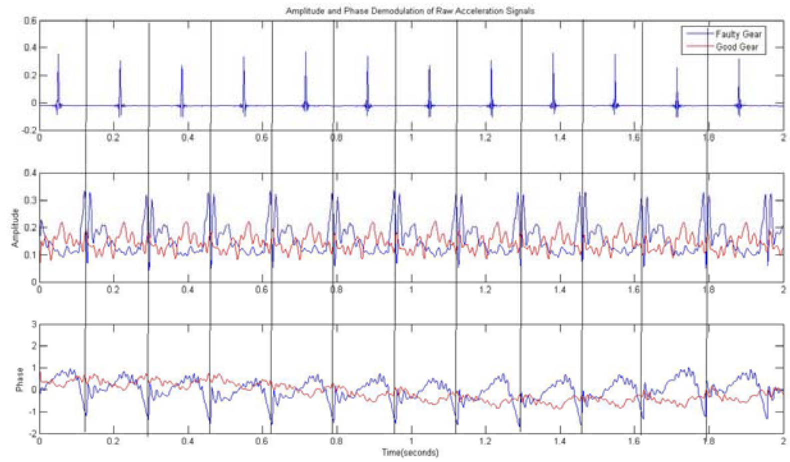
Signal Separation with Cepstrum



Use of cepstrum to remove sideband patterns

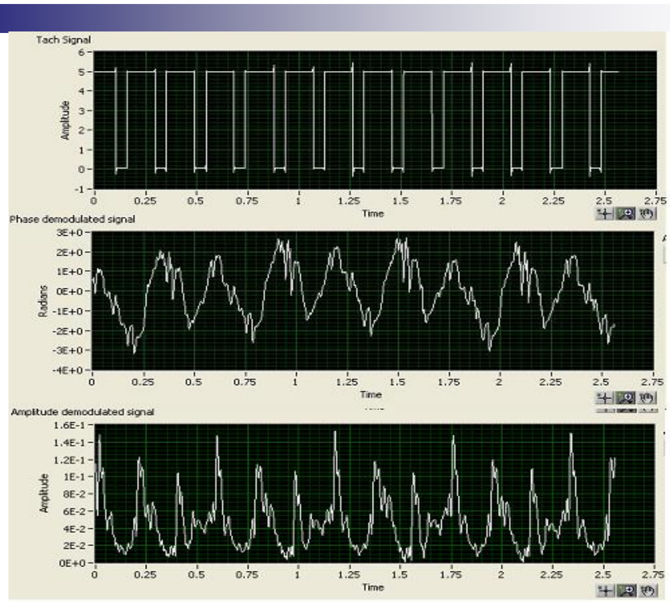
Ref: Prof. Bob Randall

Amplitude & Phase Demodulation



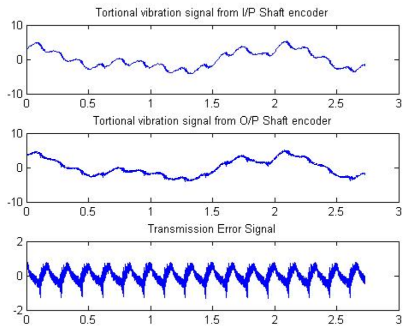
Amplitude and Phase Demodulation of raw acceleration signals from a gearbox with chipped tooth ; note both phase and amplitude demodulation work

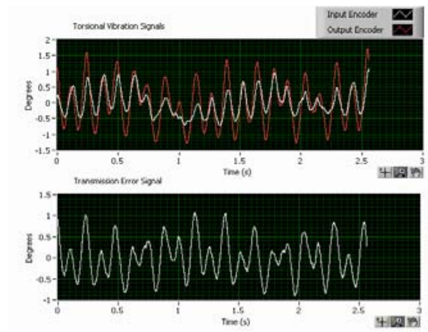
Ref: Prof. Bob Randall



Amplitude and Phase Demodulation of raw acceleration signals from a parallel shaft gearbox with chipped tooth (where phase demodulation did not work)

Transmission Error





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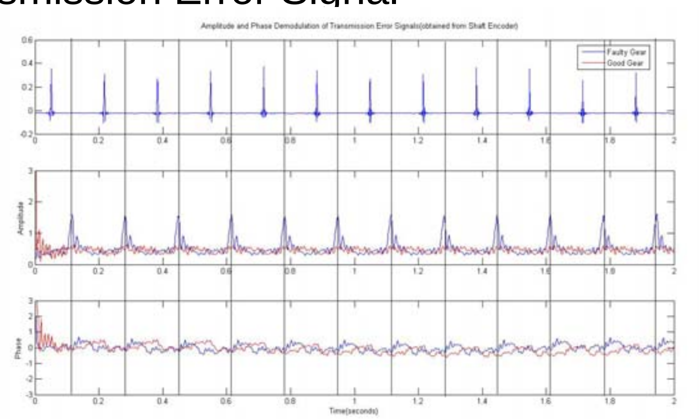
Amplitude & Phase Demodulation on Transmission Error Signal



Note that amplitude demodulation worked but phase demodulation did not work

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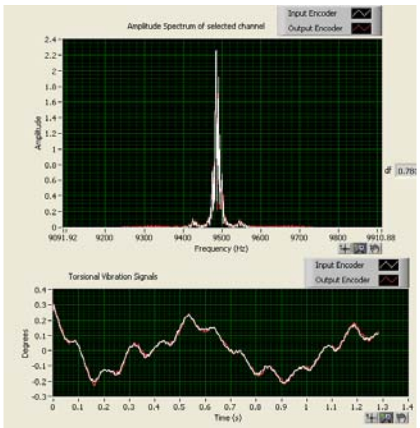
Torsional Vibration Signals obtained from TVC
with zero degree deflection



Torsional Vibration Signals obtained from TVC
with 12.5 degree deflection