Rolling-Element Bearing Analysis (R.E.B.A.) Techniques and Practices

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Vibration Institute
Piedmont Chapter – 17 September 2010

Rolling Element Bearing Analysis

Presentation Topics

Considerations in Making the Measurement

Analyzing & Experiences in the Field

Considerations in Pinpointing Problems

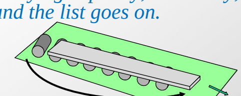
Follow-up Points and Discussion

Meaningful R.E.B. Analysis

- There are lots of product offerings, tools, and techniques available.
- Sometimes just making the choices can be a bit intimidating and overwhelming.
- We need to take away some of the “mystery”.
- We need to make the best of the situation.
- We will now examine the history, scientific terminology, and industry jargon.

Getting Down to Basics

- A bearing carries the load by round elements placed between two pieces.
- Relative motion of two pieces causes rolling, with very little resistance or friction.
- Started with logs on the ground with a stone block on top! *(Log at back was moved to front, sequentially.)*
- Rolling elements in a circular bearing are captive and do not fall out under load.
- *R.E.B. offers a good trade-off on cost, size, weight, carrying capacity, durability, accuracy, low friction, ….. and the list goes on.*




Why Do Bearings Fail?

- Poor design.
- Misapplication.
- Poor installation.
- Improper loading.
- Poor care and maintenance.

Design Engineering – Application Engineering – Maintenance

Take a Proactive Approach

- Choose the correct bearing for the application.
- Employ proper bearing installation techniques.
- Utilize proper skills in assembly, balancing, alignment, etc.
- Follow proper lubrication schedule.
- Use care in storage, shipping, and handling.
- Ensure proper operation.
- Train everyone on the value of these good practices.
- ***Take the time to do the job right!***

Facts on Bearing Life / Failure

- Less than 10% achieve design life. **
- 16% fail due to handling and installation.
- 14% fail due to contamination.
- 36% fail due to inadequate lubrication.
- 34% fail due to fatigue issues (excessive loading).
- Any extra loading (e.g. misalignment, unbalance, resonance) reduces life by a cubed function.
  - L_{10}= (16,667/RPM)* (rated load/actual load)^3
    - *10% extra loading cuts life by 1/3*
    - *20% extra loading cuts life by half!*

*** Source: SKF Bearing Journals.*

What is L_{10} Life?

- It is the life expectancy for 90% of the population.
- Full load life is estimated at 1,000,000 revolutions.
- Sounds impressive, but at 3600 RPM, this is only 4.6 hours!
- Guidelines….
  - Light load is at < 6%.
  - Normal load is 6% to 12%.
  - Heavy load is at >12%.

From a few months to years at continuous 365/24 usage.

What Do We Wish To Accomplish?

- Early detection of even the slightest fault appearing with the bearing.
- Avoidance of any down time and secondary damage due to bearing failure.
- Pinpoint the faulty component and possible cause of the excessive vibration.
- Decide a corrective course of action.
- Follow-up and verify.

Familiar Key Elements: ***Detection – Analysis – Correction – Verification***

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The Detection Technologies

- Vibration analysis and acoustic emission.
- Oil and wear particle analysis.
- Infrared thermography.

Each technology has its place and should be used where appropriate. (Many times, they are complementary.)

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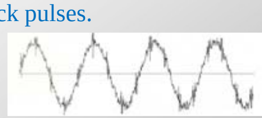
Vibration and the Sources

- We can typically break vibration down to **4** main components:
  - Forced vibration due to unbalance, misalignment, blade and vane pass, gear mesh, looseness, impacts, resonance, etc.
  - Resonance response due to impacts.
  - Stress waves or shock pulses.
  - Frictional vibration.



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It's All About Pattern Recognition

- Vibration measurements provide us with four basic spectrum (FFT) patterns:
  - Harmonics - Almost always caused by the TWF shape.
  - Sidebands - Due to Amplitude or Frequency Modulation.
  - Mounds/Haystacks - Random vibration occurring in a frequency range.
  - Raised Noise Floor - White noise or large random events.

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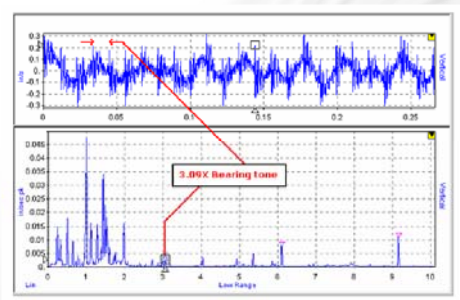
TWF to FFT



Complex
to
Simple

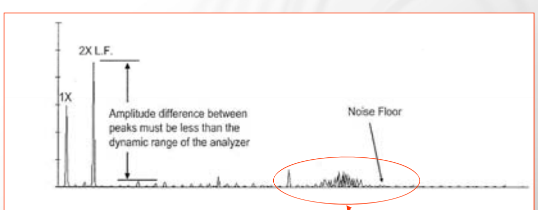
"The Signature"

What Are We Looking For?

- Detection of a even the slightest metal-to-metal contact from impacting components or inadequate lubrication in a bearing.
- A slight ringing caused by a bearing fault resonating a natural frequency in the machinery setup.
- Presence of high-frequency, low-energy vibration.
  - Sometimes noted as raising the "carpet level" in the noise floor in acceleration readings – especially at high frequency.
- Capability to detect an incipient failure with senses that transcend normal human abilities .. sight, sound, touch, smell, etc.

Note: It is not important as to what natural frequency is excited; the measurement just needs to be repeatable.

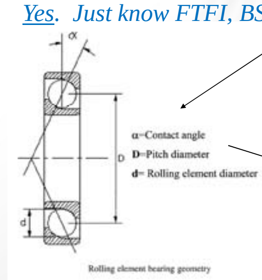
Tell-Tale Signs in Acceleration



Presence of very small peaks at High Frequency!

Isn't It Just Math?

Yes. Just know FTFI, BSF, BPFO, and BPFI.



$$w_c = \frac{n}{2}\left[1 - \frac{d}{D}\cos(\alpha)\right]$$

$$w_b = \frac{n}{2}\left(\frac{d}{D}\right)\left[1 - \left(\frac{d}{D}\right)^2 \cos^2(\alpha)\right]$$

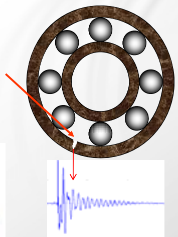
$$w_{bp} = \frac{n}{2}N_b\left[1 - \frac{d}{D}\cos(\alpha)\right]$$

$$w_{bpi} = \frac{n}{2}N_b\left[1 + \frac{d}{D}\cos(\alpha)\right]$$

(assumes a fixed outer race)

A Look at Geometry …

Impacts per Revolution



Ball Bearings

Roller Bearings

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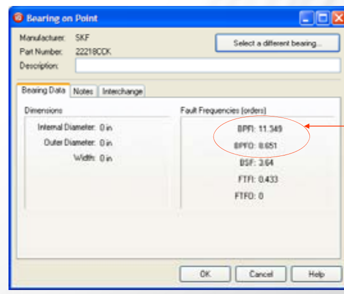
Fortunately .. It’s All Worked Out



Note: BPFI + BPFO = Number of Elements; typically a 60/40 relationship.

(See data at left. 11.349 + 8.651 = 20 rolling elements.)

Also, sometimes estimated as:

BPFI = $N_B/2 + 1.2$
BPFO = $N_B/2 - 1.2$

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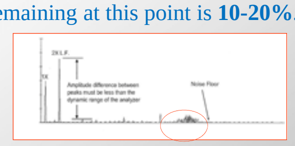
What Are The Typical Failure Stages?

- STAGE 1:
  - Presence of ultrasonic frequencies (typically well above 5KHz) that are barely detectable.
  - Very low amplitudes appearing in the acceleration measurement.
  - Life remaining at this point is **10-20%**.



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Typical Failure Stages?

- STAGE 2:
  - More ringing occurring, and presence of frequencies of 500Hz to 5KHz.
  - Fault frequencies show up with modulation (sidebands).
  - Time waveform of acceleration shows impacting (flat-topped or notched).
  - Bearing life down to **5-10%**.

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Typical Failure Stages?

- STAGE 3:
  - Energy spreads more down the spectrum.
  - Defect frequencies begin to be more prominent.
  - More harmonics and sidebands show up.
  - Wear tend to flatten out peaks and patterns.
  - Bearing temperature increase is now apparent.
  - *It is time to order parts and start an action plan!*
  - Bearing life is now **5% or less**.

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Typical Failure Stages?

- STAGE 4:
  - 1X energy begins to increase as clearance is quite noticeable.
  - Broadband spectral noise is evident by a raised noise floor.
  - Failure is eminent!
  - **1%** life is remaining at best.

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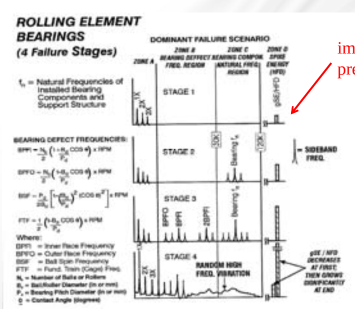
What Do The Experts Say?



Courtesy of Technical Associates of Charlotte ©

impacts and ringing present

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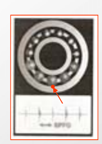
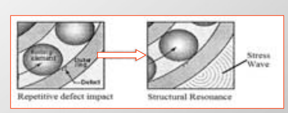
What Causes This Vibration Energy?

- Contact between two metal surfaces.
- A shock (or pressure) wave is created.

  - Analogy is the wave set up by an earthquake or tsunami.
  - A ripple from a pebble tossed in a pond is another example.
- Resulting signal propagates through the metal surfaces when there are no air gaps to filter (good metal-to-metal contact).





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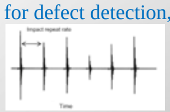
How Can We Detect Early Signs?

- Special instrumentation and detection circuits.
- Special signal processing.
- Detection of small spikes with short duration and ringing characteristics.
- A small tell-tale signal in the presence of lots of noise and higher amplitudes (a high dynamic range > 95dB).
- Accelerometer with a solid mounting.
- Good measurement practices.
- Special measurement for defect detection, plus normal readings in 3 axes.



How Have Solutions Suppliers Addressed This Need?

- Lots and lots of competitive and complementary offerings, some dating back to the early 70's:
  - Spike Energy™ and Spike Energy Spectrum™
  - ESP™ (Envelope Signal Processing)
  - HFD ™ (High Frequency Detection)
  - SEE ™ (Spectral Emitted Energy)
  - PeakVue ™
  - Shock Pulse ™
  - Stress Waves
  - Enveloping (or Demodulation)
  - Cepstrum

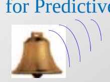
The Choices …

Company	Analyzer Model#	Product Name	Frequency Range	Sampling Rate	Sensor	Diagnostic Output
Commtest www.commtest.com	vb3000™ and vbSeries™	Demodulation	20 Bands up to 20 kHz	up to 51,200/sec.	stud or magnet	Demodulation Spectrum and Waveform
DLI - Azima www.dliengineering.com	Watchman®, DCX™, XRT	Envelope Demodulation	1250-10,000 Hz	41,000/second	stud mount	SP, WF, Overall, Crest Factor
Emerson Process Management (CSI) www.compsys.com	2130 Machinery Health Analyzer	PeakVue®	6 High Pass Bands 500- 20,000 Hz	51,200/second	stud or magnet	Waveform peak-peak, SP, WF, Auto Correlation
GE Energy (Bently Nevada) www.bentlynevada.com	Snapshot™	Acceleration Enveloping	5 Bands 400-32 kHz.	76,000 and 102,000 samples/second	stud or magnet, hand-held	Direct peak-peak, direct RMS SP and WF
Pruftechnik www.pruftechnik.com	VIBXPERT®	SPM® Method	Band around 36 kHz	135,000/second	stud or cam lock, magnet	dBmax, dB carpet, SPM WF & SP decibel level shock value
Rockwell Automation www.rockwellautomation.com	EnPAC® 2500	Spike Energy™ & ESP™	6 HF Bands, 1-5 kHz. 5 Band Pass up to 20 kHz	51,200/sec.	stud or magnet, special sensor	Spike Energy Peak-to-Peak, Spike Energy SP & WF
Shaeffler Group (FAG) www.fag.com	Bearing Analyser III	Acceleration Enveloping	2 High-Pass Bands 750 Hz. and 2 kHz	Max sample rate 200,000/second	stud or magnet	Carpet level for envelope signal
SKF Condition Monitoring www.skf.com	CMVA 65 Microlog®™ Analyzer	Acceleration Enveloping & SEE™	5 Bands up to 40kHz 250-350 kHz	100,000 for most products	stud or magnet	ENV Average, ENV Peak, SP, WF, & SEE level
SPM Instrument www.spminstrument.com	Leonova™ Infinity	SPM® Method	32 kHz (requires special sensor)	1000 shocks/sec. (tube) 50 shocks/sec. (surface)	stud, glued, permanent, hand	dBmax, dB carpet, SPM WF & SP, decibel level shock value
SWANTECH www.swantech.com	SWANguard™	SWAN™	38.5 kHz. Carrier +/- 7 kHz Band	20,000/sec.	bolt-on, epoxy or stud mount, glued	Stress wave peak amplitude and Pulse train, stress-wave energy

Most of the manufactures listed offer permanent monitoring systems with high frequency detection circuits
SP = Spectrum, WF = Waveform

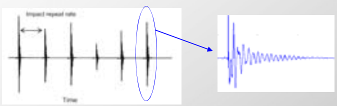
Is There a Common Thread?

- All methods are based on a fundamental concept: ***There are repetitive impacts in the machine structure that indicate bearing faults, gear damage, looseness, cavitations, and similar faults.***
- Machine/bearing resonances (or sensor resonance) are excited by the impacts – similar to striking a bell.
- Repetitive fault frequencies can be identified with special signal processing – filtering, peak detection, and frequency analysis.
- Careful measurement and collection methods are essential to enable this technique.
- Advanced signal processing technology and instrumentation available today make this a proven analysis tool in routine data collection programs for Predictive Maintenance (PdM).



What Do We Need To "See"?

- Spikes from impacts.
- Ringing from a natural resonance being excited.
- Demodulation (or other method) to determine and "see" the repeated fault frequency.
- Frequency Determination on 'Impact Rate' to isolate the fault.



the impact and ringing

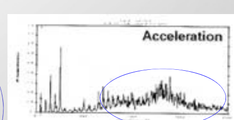
What Are the Basic Requirements?

- Solid Transducer Mounting.
- Mounting Target and Orientation Maintained.
- Mounted in Load Zone of Bearing Housing.
- Best Possible Mechanical Interface for Transmission of Energy.
- High Frequency Energy Detection Method.
- Detection of Repeated Fault and Ringing Condition.
- Ability to Strip Out Low Frequencies Associated with Actual Running Speed.
- Ability to Demodulate (Envelope) Signal or Determine the Peaks of the Repetitive Fault Frequency.
- Ability to Detect Repetition Fault Frequency.
- Ability to Show Resulting Signature (FFT) and Compare the Pattern to Published Data.

High-pass – Repetitive Peaks in TWF – Low-pass – FFT

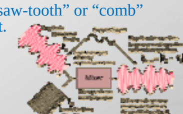
The Measurement Challenge

- The mounting method is of key importance.
- We cannot "see" high frequency vibration unless the mount is a solid mechanical interface.



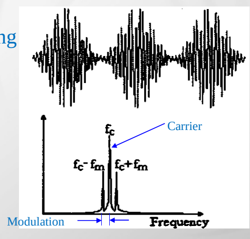
What Does "Demodulation" Really Mean?

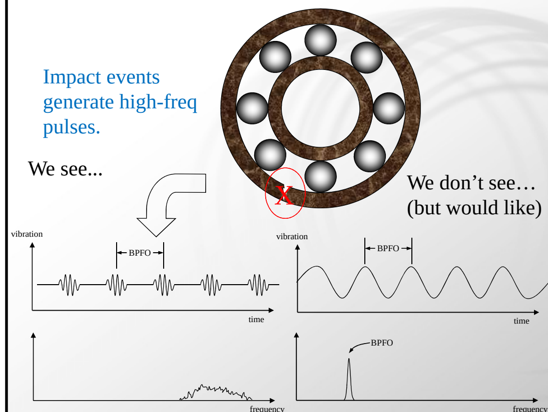
- *It is analogous to stripping out the information from an AM radio broadcast.*
  - *Spanning the band for the station frequency (540-1600 KHz) and picking off the broadcasted signal.*
- First need to incorporate a high-pass or band-pass filtering.
- Eliminate any high amplitude signals associated with 1X and multiples up to about 10X.
- Include only the fault frequencies exciting inherent resonance.
- Intensify and draw out repetitive components of the fault.
- Convert to frequency for display of the pattern.
- Amplitudes will show up as a distinctive "saw-tooth" or "comb" harmonic pattern of the actual bearing fault.



More on Amplitude Modulation

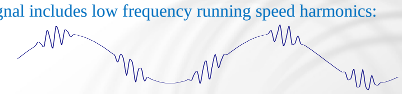
- Amplitude Modulation (AM)
  - One frequency (carrier) is getting louder and softer at another frequency (the modulating frequency).
  - AM is mono. Mono is 'one', which implies **one** sideband on each side of the carrier.





The Instrument Signal Processing …

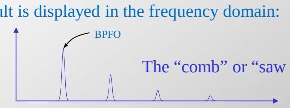
The raw signal includes low frequency running speed harmonics:



These are removed by band-pass filtering:

Then envelope detection is applied:

Finally the result is displayed in the frequency domain:



The "comb" or "saw tooth" pattern.

Can The Reading Be Trended?

- *Yes, but consistency of measurement is of utmost importance.*
  - Same hardware.
  - Same measurement location.
  - Solid mounting in good mechanical transfer path.
  - Same conditions.

Case History Example

- Automotive paint facility.
- 250 HP motors running 6-foot bladed exhaust fans.
- Motor running at 1792 RPM.
- Fan belt driven and running at 820 RPM.
- Bearings known.
- Excessive vibration reported.
- Initial measurements made of vibration with acceleration, velocity, and demodulation.
- Source of problem is identified, corrective action is recommended.
- Bearing SKF 22218CCK changed out at next production break.
- Let's take a look at initial results first, then Before/After comparisons.

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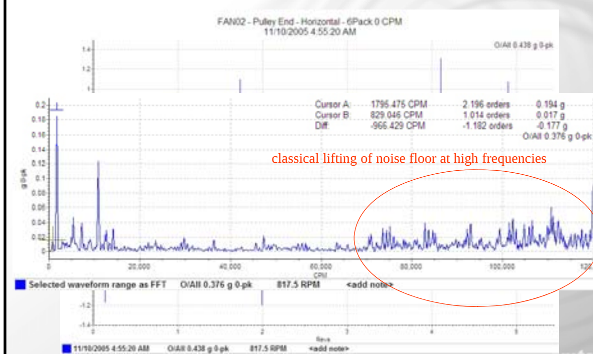
First, Acceleration



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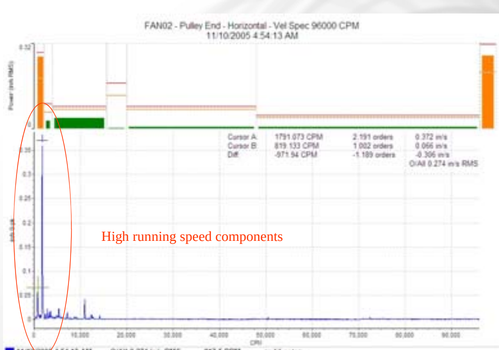
Next, Velocity



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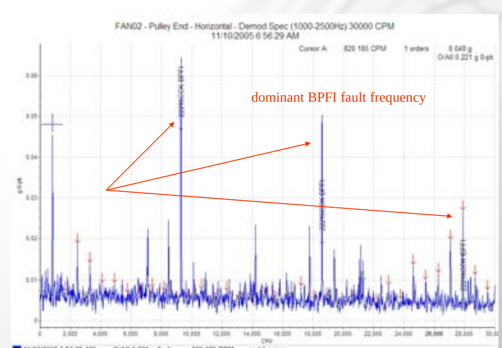
Now, Demodulation



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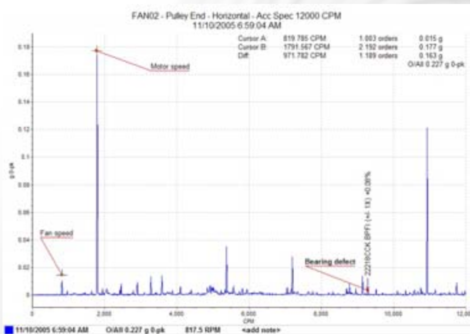
After the Fact, but not obvious



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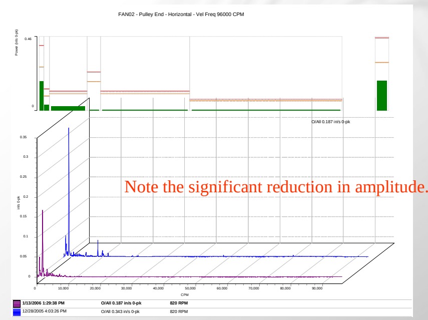
Velocity – Before and After



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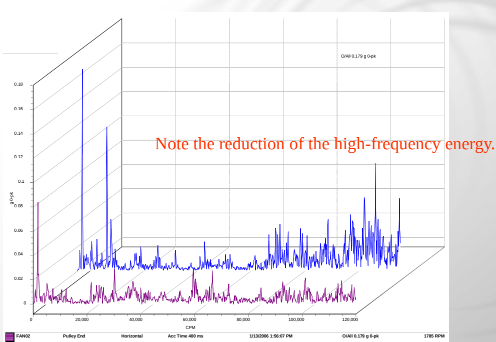
Acceleration – Before and After



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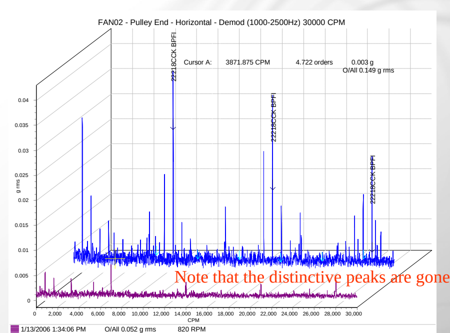
Demodulation – Before & After



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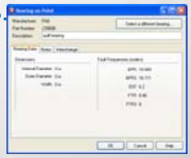
Another Recent Finding

- Low speed machine turning at 394 RPM.
- Bearing known as FAG 23906B.
- Fault frequencies known:
  - BPFI is 18.889
  - BPFO is 16.111
  - BSF is 6.2
  - FTFI is 0.46
- Low vibration amplitudes, but somewhat noisy.
- High frequency acceleration data was taken along with routine measurements, no demod.



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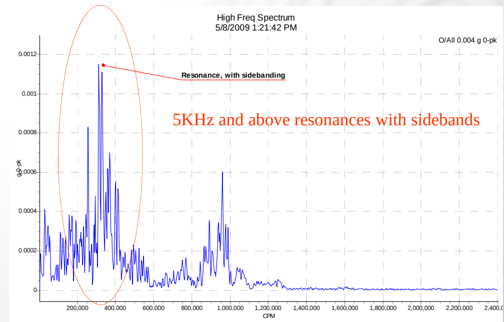
First, The High Frequency Data



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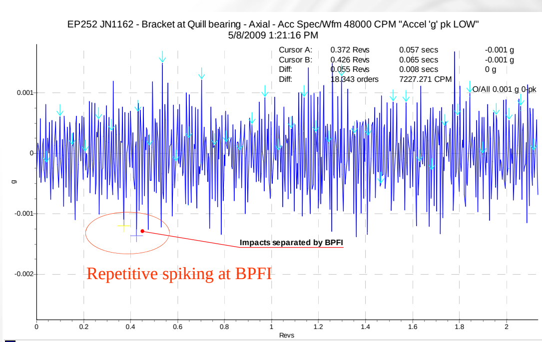
Next, the Time Waveform



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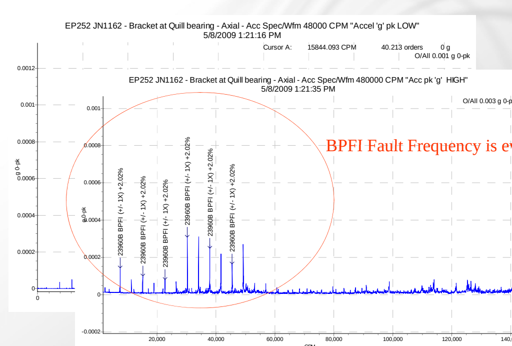
Finally, the FFT with Overlays



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Pre-requisites and Procedure

- Bearing part number(s) must be known.
- Fault frequencies must be known and preloaded.
- Running speed must be accurately recorded.
- Bearing faults excite natural resonances in the machine components or transducer.
- The fault frequency is recurring.
- A technique is available to detect the repetition rate in time.
- The fault frequency (if present) can be shown in an FFT display with bearing data overlays.

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Summary Remarks

- Machinery vibration measurements in time waveform and spectrum can provide early (tell-tale) signs of rolling element bearing defects.
- Special signal processing techniques (now available in most portable data collectors) can detect impacting spikes and pinpoint a specific fault frequency.
- Comparing the resulting signature (pattern) to published fault frequencies can pinpoint the root cause of the problem.
- Field experiences in PdM over 30 years have proven the concepts to be very accurate and reliable.
- Considerable cost savings (in maintenance and production) are afforded by use of this technology.

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Questions / Discussion
on
Rolling Element Analysis?

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