Improving Hydroturbine Health Monitoring using Advanced Telemetry

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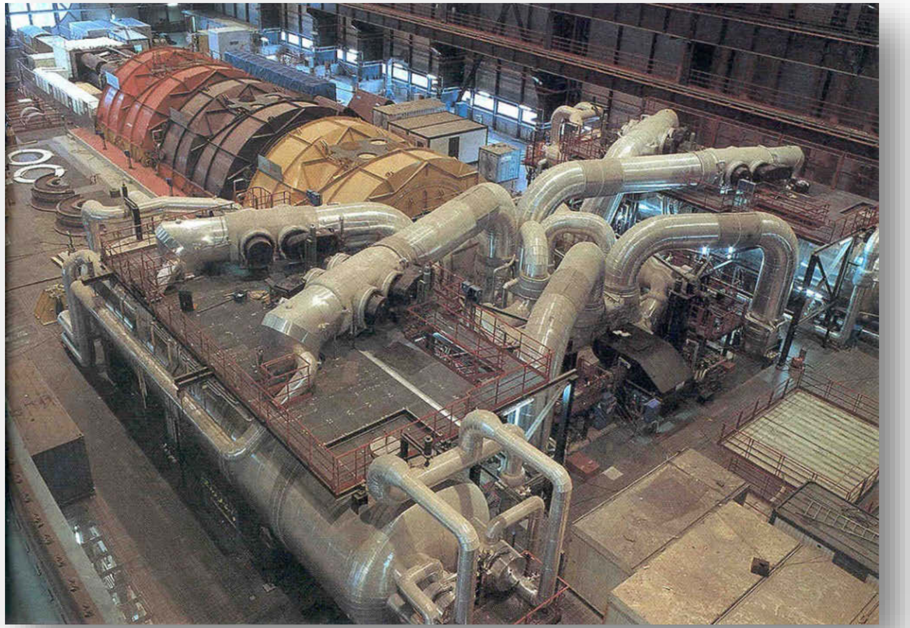
Presentation Outline



- Better signals give real-world value.
- Sensor Technologies.
  - Wireless and wired telemetry.
- Software infrastructure.
- Field data results.
- Practical sensor fusion and multivariable diagnostics.

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Data and real value perspective

- **Why is this EPRI project of value to utilities?**

- State of the art sensors give a deeper perspective on data dynamic range and sensitivity.

- There is value in monitoring signals that were not previously considered practical.

- Parts of the turbine-generator system can be measured that were previously unmonitored.

- Key concepts:
  - *Sensor dynamic range =* ***Early detection.***
  - *Frequency bandwidth =* ***Comprehensive dynamic data from fewer sensors.***
  - *Multi-sensor fusion =* ***Cause/effect and <u>actionable engineering information</u>.***

"But we already have sensors and APR."

- My plant monitors operational sensors already.
  - Sweet deal. We will not disrupt what is working in place.
- Traditional vibration probes, temperature, and operational sensors can miss information that helps diagnose root causes and ultimately save cost.
- New sensors must not burden plant operations or cause additional work;
  - **They must support better planning and engineering decisions.**
- **What makes these new sensors better?**

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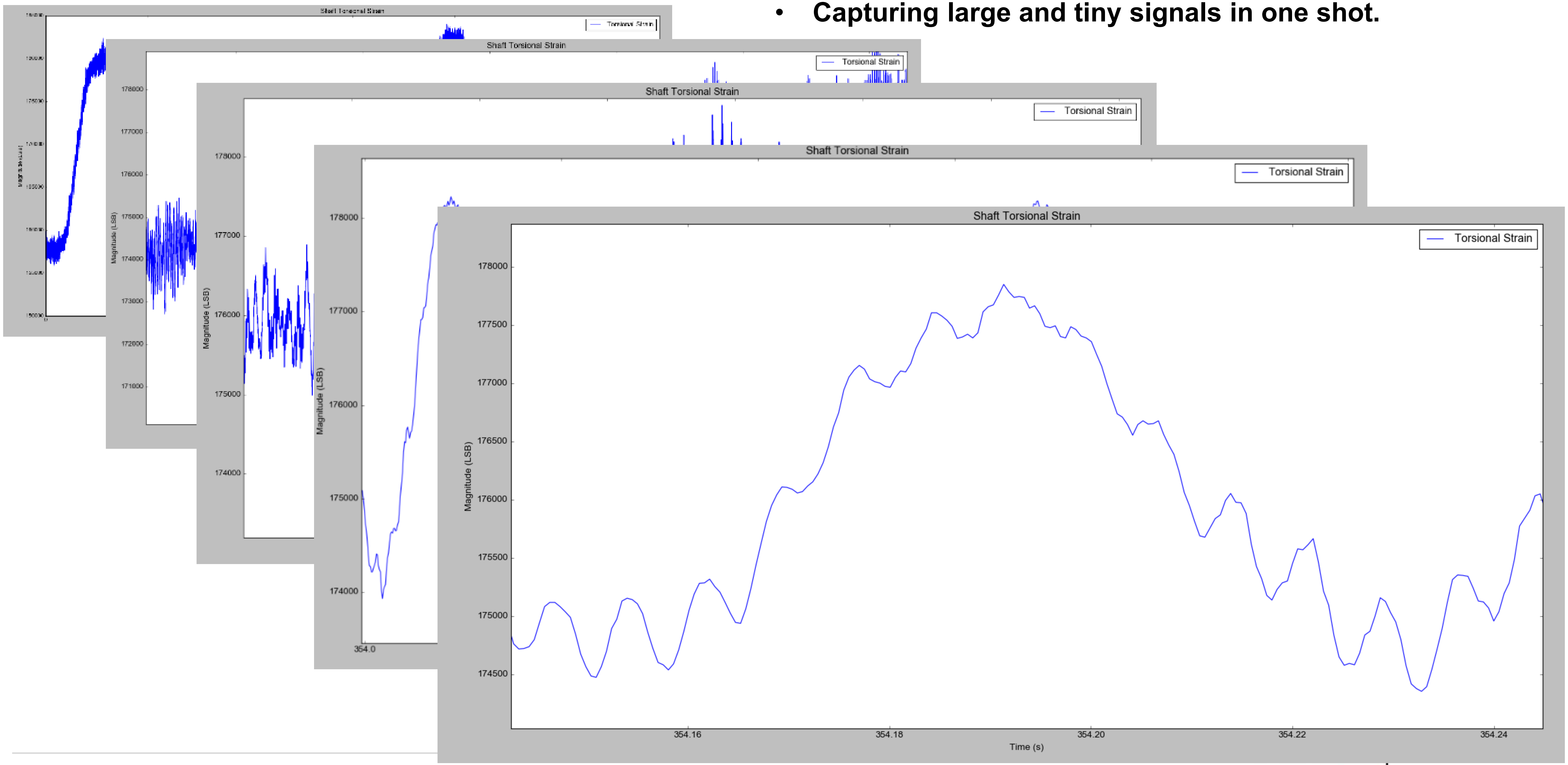
Dynamic range. Do you have it?

- **Capturing large and tiny signals in one shot.**



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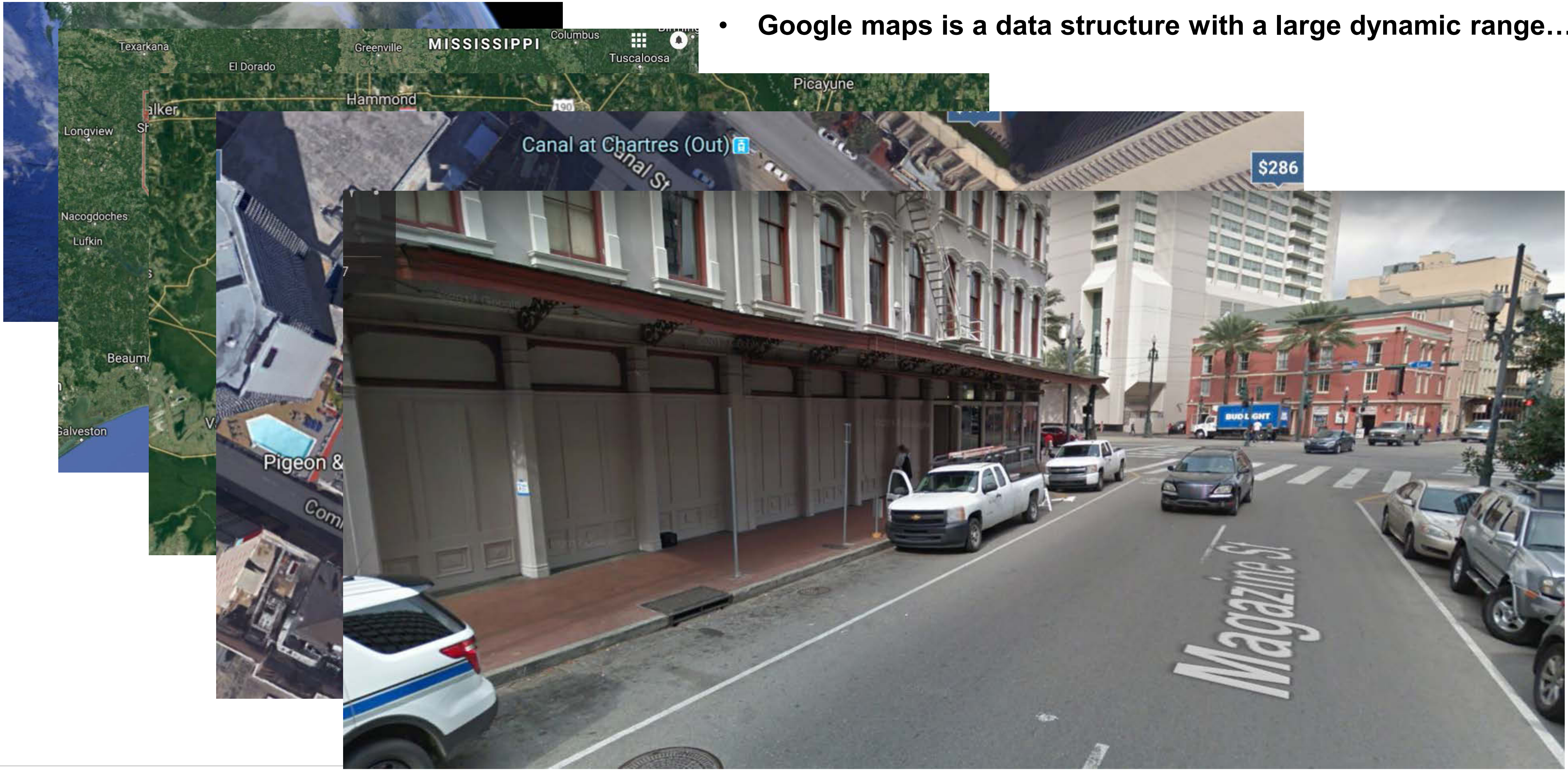
What Dynamic Range actually means to humans



- **Google maps is a data structure with a large dynamic range…**

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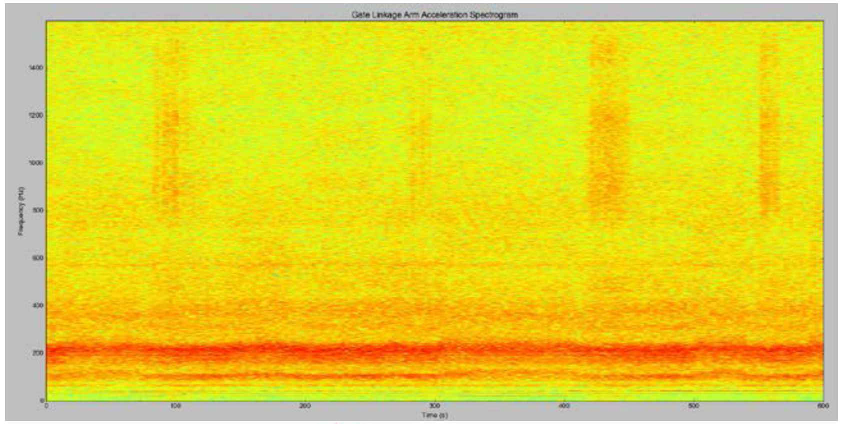
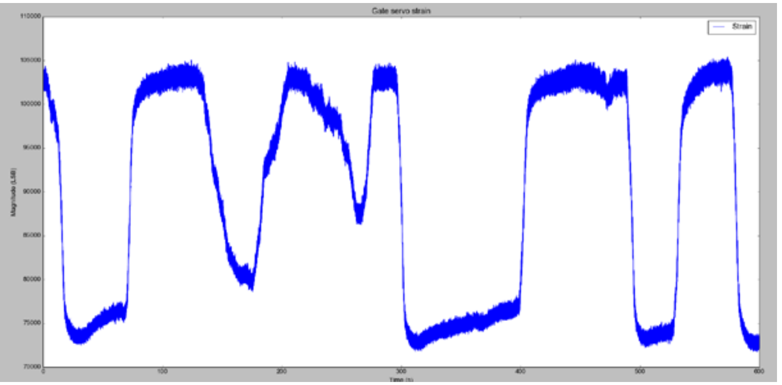
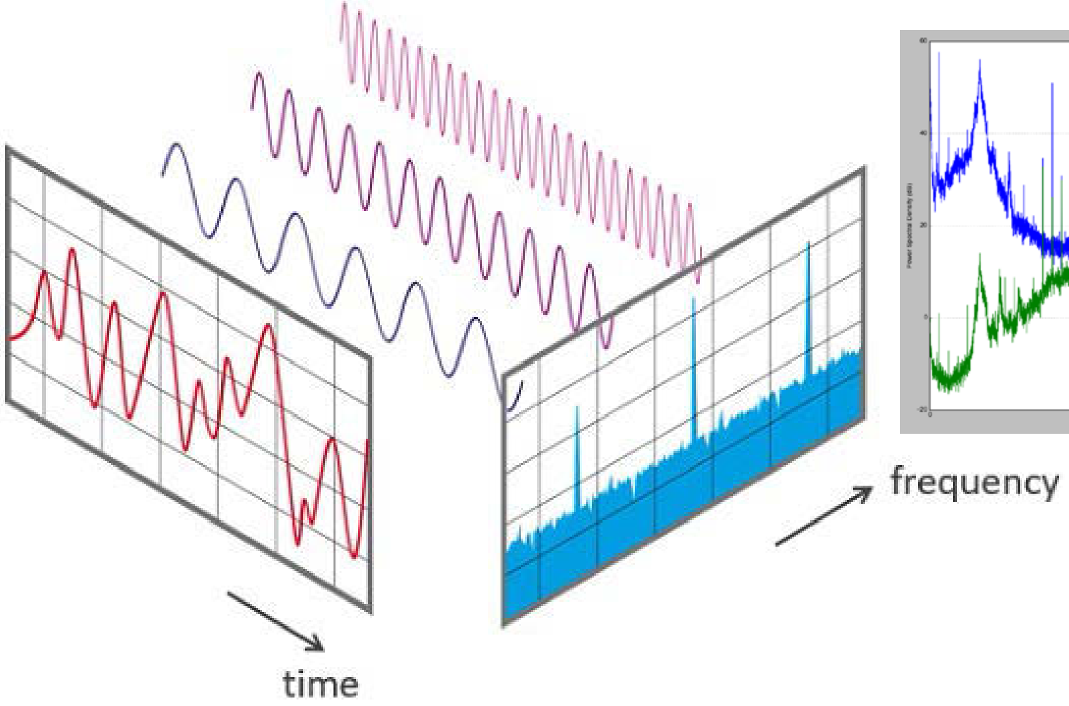
Data analytical facets

Time-frequency (spectrogram)

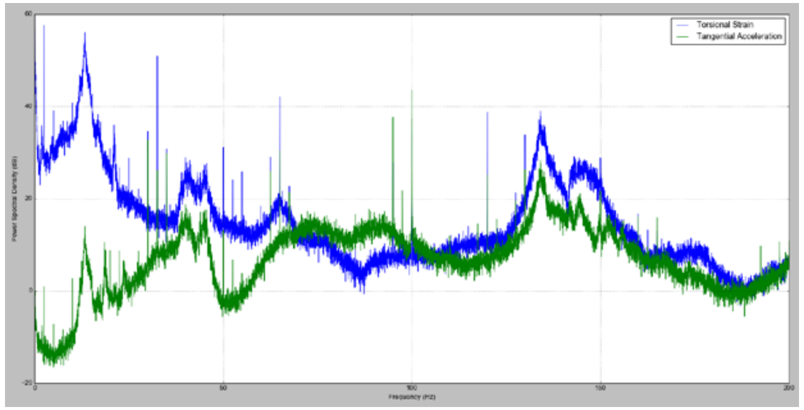


Time domain





Frequency domain



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Extracting information

- Time domain analysis is good for:
  - Wave shape and understanding motion behavior.
  - Assessing continuity (e.g. jumps in position, looseness, intermittent events).

- Time-frequency plots are good for:
  - Identifying when a vibrational behavior changes.
  - Pinpointing what vibration modes (frequencies) of a machine are associated with an event.

- Frequency domain analysis is good for:
  - Understanding how a machine responds to forced inputs.
  - Evaluating if the machine is in a safe operating condition (e.g. P65 steam turbine results to measure if forcing functions are away from resonant frequencies).

Hearing the pin drop.

- Where Maps uses a composite of different data sources (satellite, aerial, ground level) **the sensors discussed today contain this range of information in a single signal.**
  - This is fantastic, but requires advancements in data processing of the data to match.
  - Classic APR, SCADA, and plant historian systems cannot intake the big data being produced by the modern telemetry.
  - A bridge is required to extract the value without burdening legacy systems.
- **EPRI is evaluating more modern APR capable of digesting fast data.**
  - Value-oriented approach to provide analytical results to the plant, not raw data.
  - Focused on what the data means and how it is useful for decisions.
  - Not forcing operators to deal with massive data.

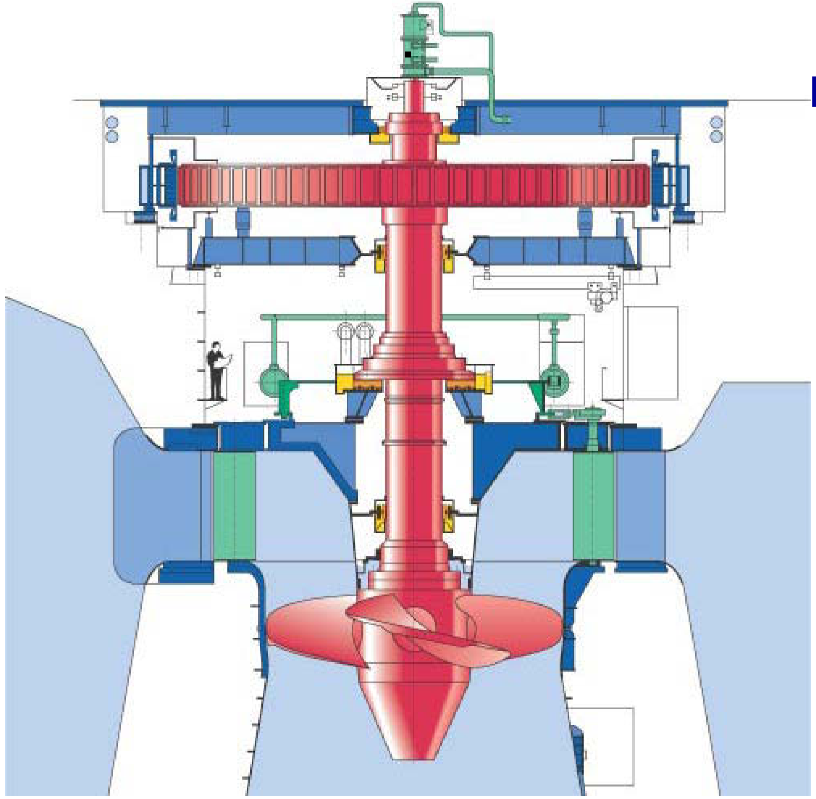
Sounds great, but

The EPRI monitoring vision

- EPRI applied better data sources…
- Turning huge data into operational value re

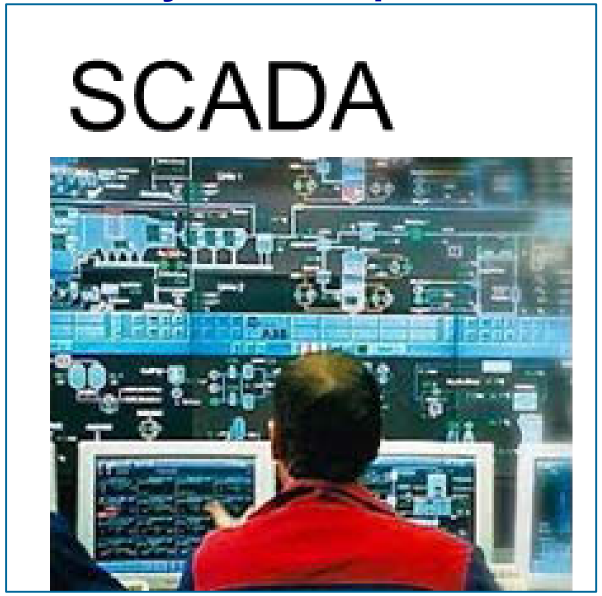
Create manageable information from advanced sources WITHOUT disrupting existing infrastructure.

Advanced sensors on the power unit.



High speed analytics local at the p er unit.

Data results & alarms sent to legacy systems in-place.



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Analytics & Automated pattern recognition (APR)

- More advanced APR can do time-frequency analysis.
  - Dealing with high frequency and high resolution signals.
  - Producing results from advanced telemetry sources.

- Analyzers can be based on learned parameters or physical models. In practical use cases, both are applied to make sense of data.
  - **The analytics process is what leverages the data to make engineering value.**

- In a turbine-generator, all parts of the unit interact dynamically. Signals are shared through the rotor, foundation, structure, water. Moving as a symphony of vibration.
  - Analyzer processes act much like the human brain listening to music.
  - With time-frequency data the job of APR is to recognize if the components in the physical system are playing “out of key”.

Sensor technologies for primary asset monitoring

- TDMS (Turbine Dynamics Monitoring System)

- State of the art stationary sensors including:
  – Field mountable strain sensors.
  – Tri-axis accelerometers.
  – Surface wave vibration sensors.

- **What u got?**

On-rotor telemetry; TDMS overview

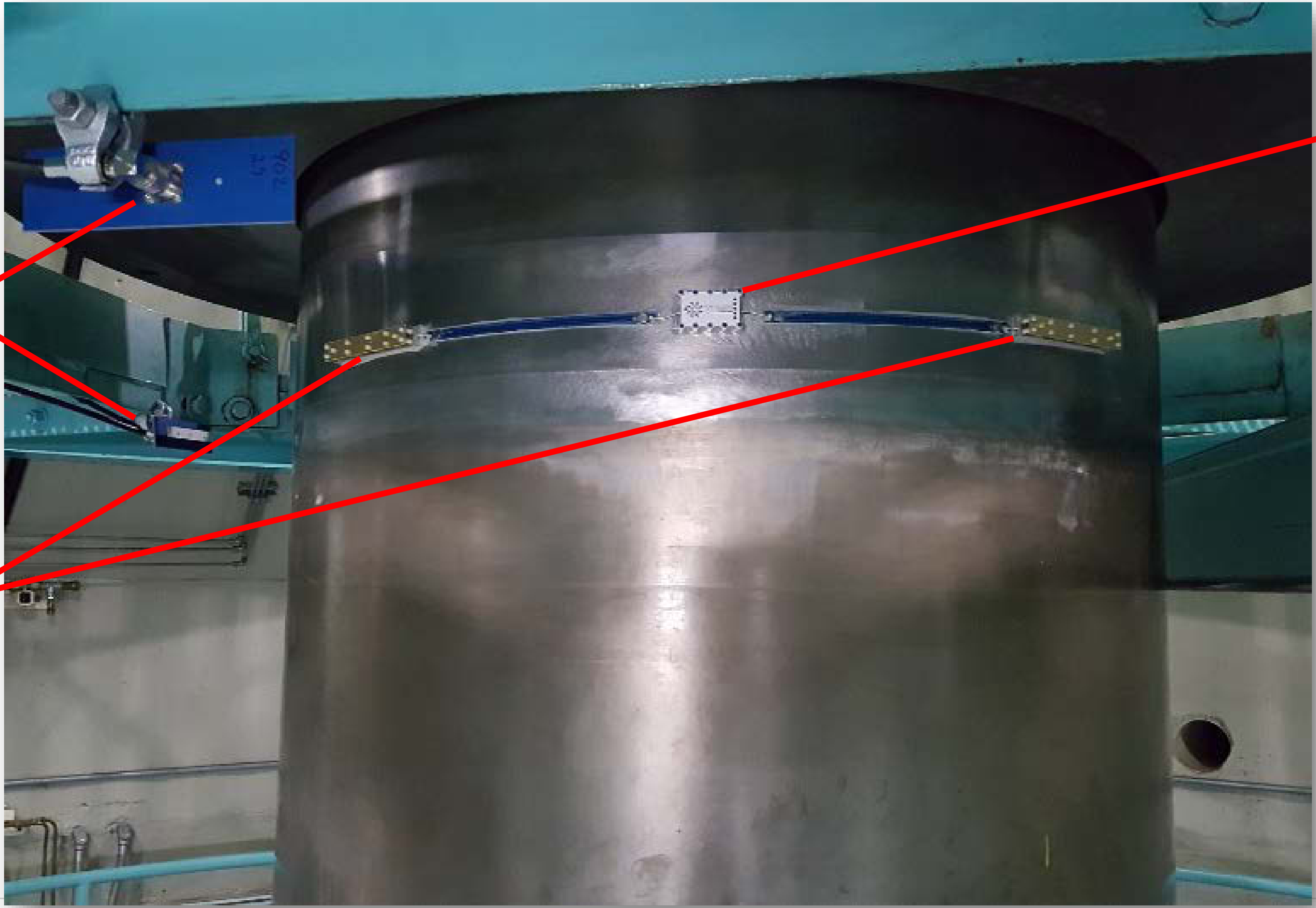
TDMS
TURBINE DYNAMICS MONITORING SYSTEM

- Torsional strain
- Tangential acceleration
- Lateral (bending) strain
- Radial acceleration

- Wireless battery free
- No welding, drilling, or straps
- User friendly DAQ software
- Simple post processing

Hydro rotor mounting of TDMS

Stationary antennas

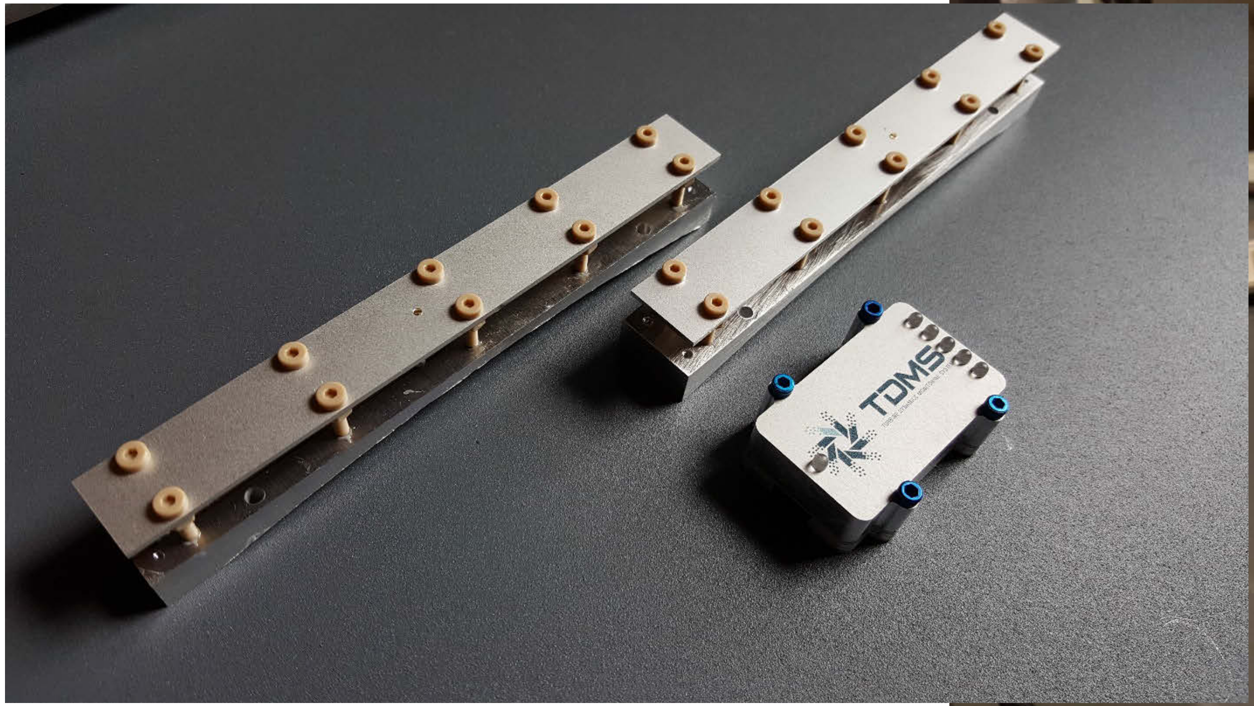


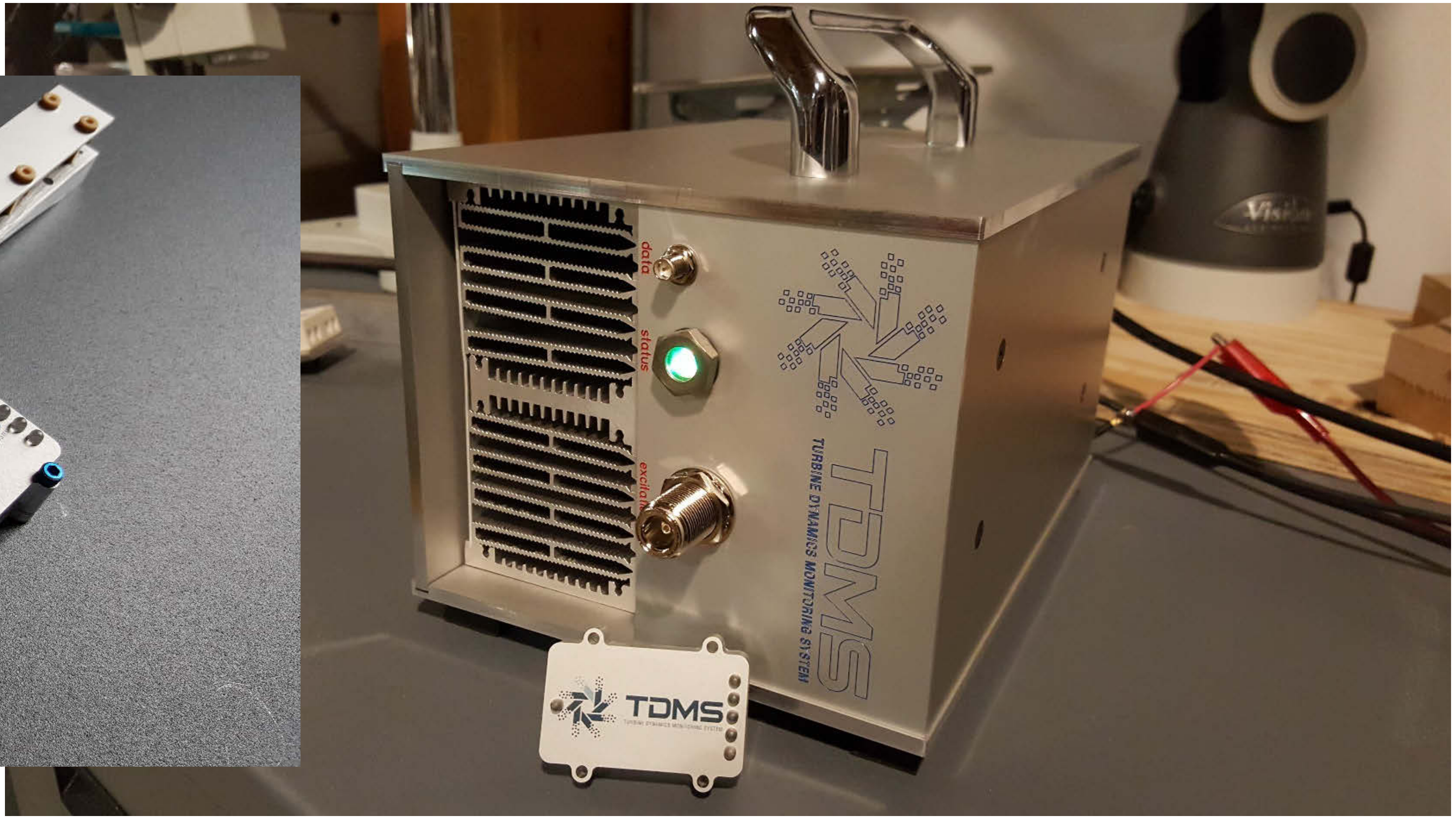
TDMS telemetry

Rotating antennas

Hydro rotor mounting of TDMS

TDMS Components





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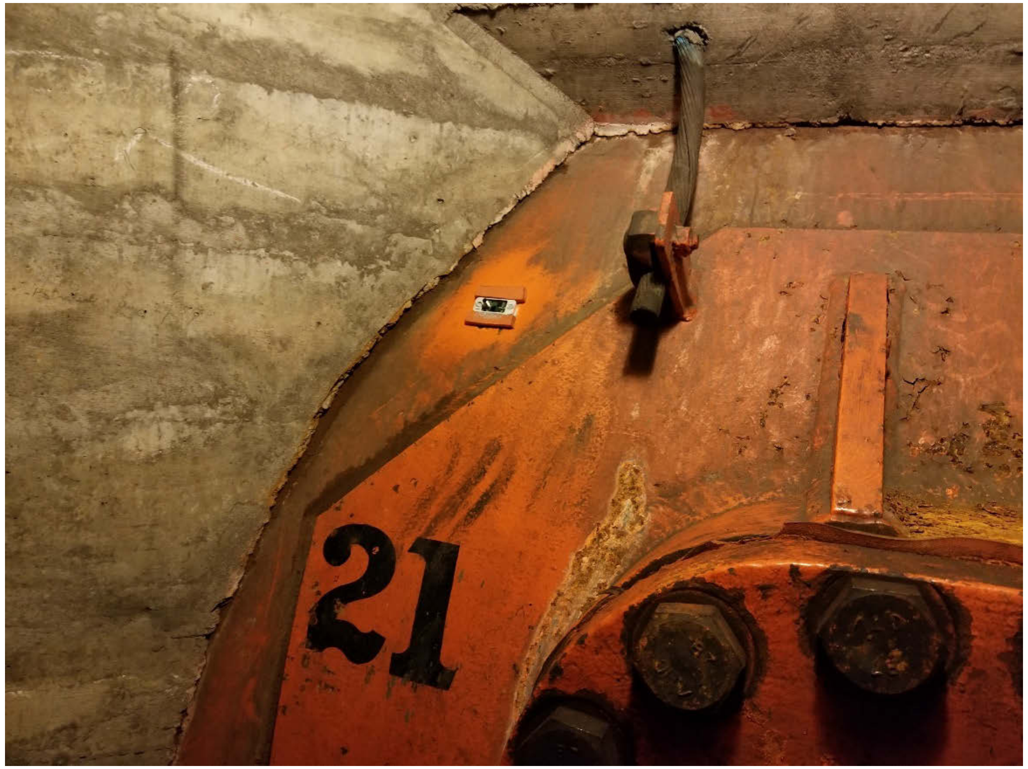
Stationary strain sensors

- Gate drive servo strain
- Scroll case strain
- Anywhere…

- Fully digital.
- No setup, soldering, etc.
- Deploy in real environments.



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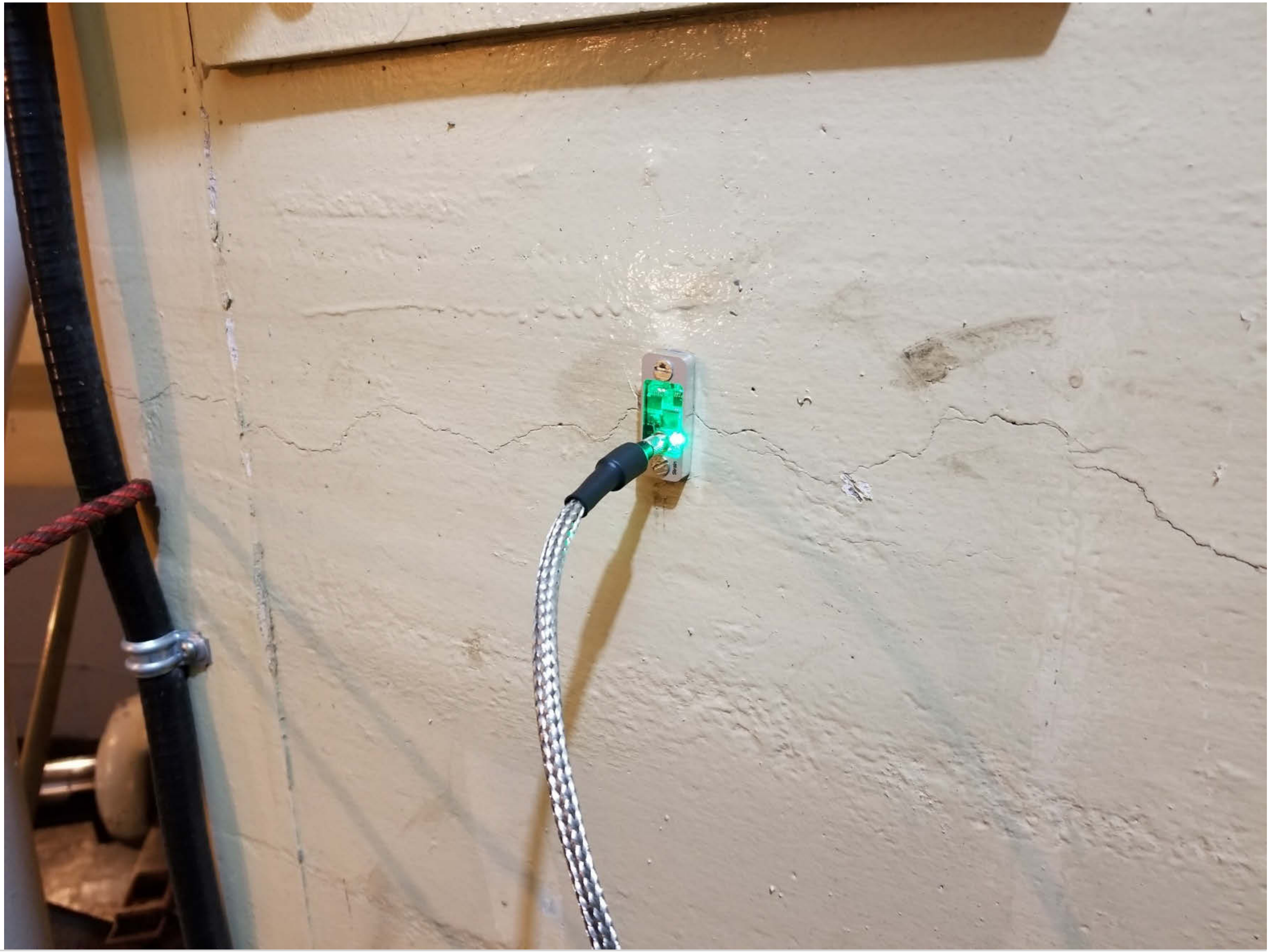
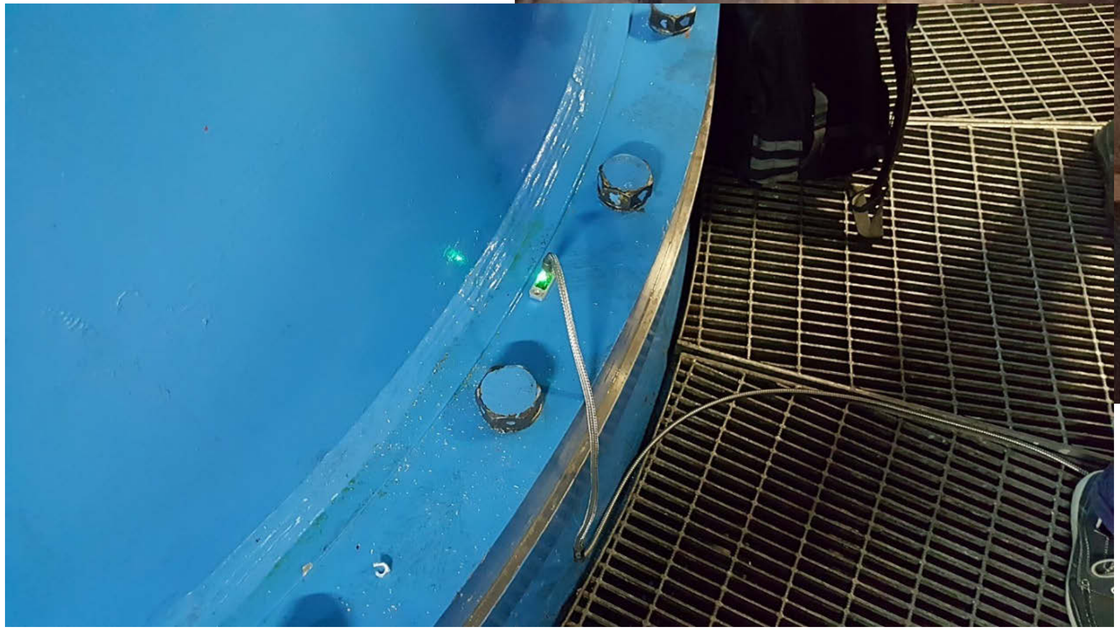
Stationary strain sensors

- Foundation measurement.
- Relevant for vibration.
- Data discussed later…



Stationary accelerometers

- Gate linkage measurements.
- Cavitation and gate vibration.



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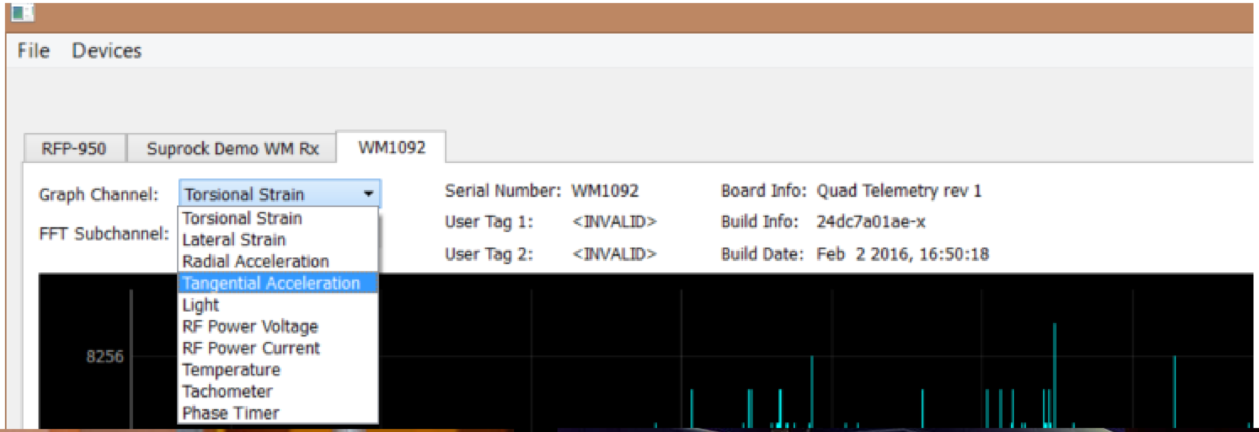
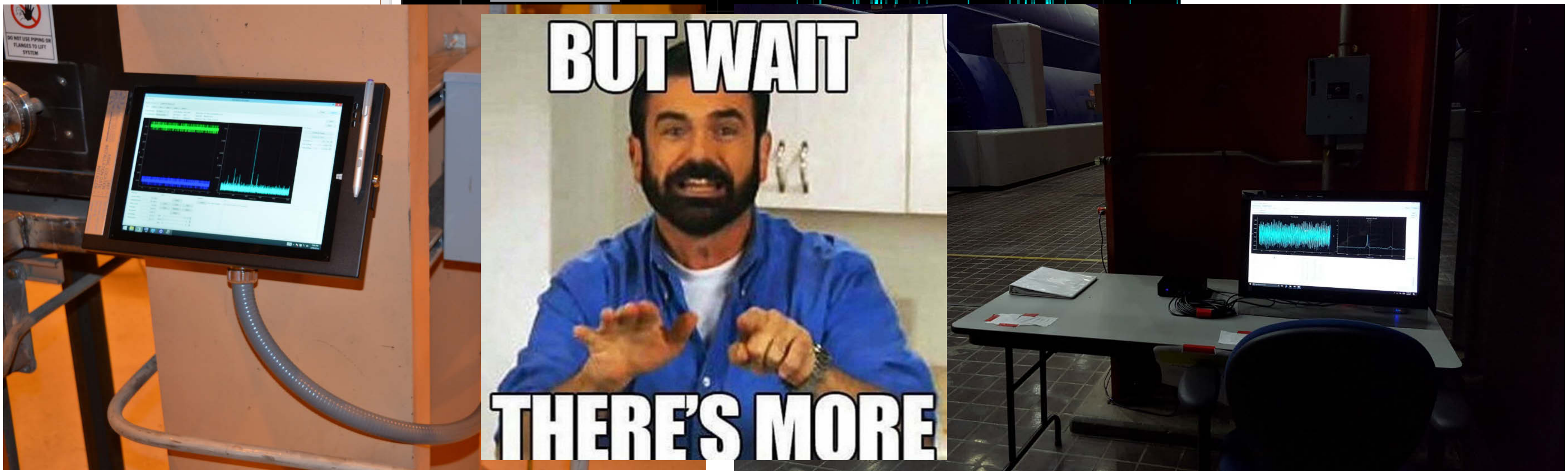
Wireless asset monitoring for auxiliary equipment

- Plant-side monitoring in support of the primary turbine-generator asset.
- Emerging concept to deploy wireless monitoring for turbine-generator plant peripheral equipment like hydraulic pumps, fans, etc.
- Tri-axis acceleration up to 25.6ksps, Strain, etc.

Data Acquisition Interface. Unifies sensors discussed above and more…





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"Any program is only as good as it is useful"- Linus Torvalds.

- The infrastructure being developed in hardware is supported by software that does not limit adoption or configuration.
  - Completely free to EPRI members and developers.
  - Suprock offers open communication libraries.
  - Source code with no license dependencies (not tied to Labview, Matlab, or any other third party software).
  - Runs on Windows, Linux.
  - Data streaming and plotting software are available.

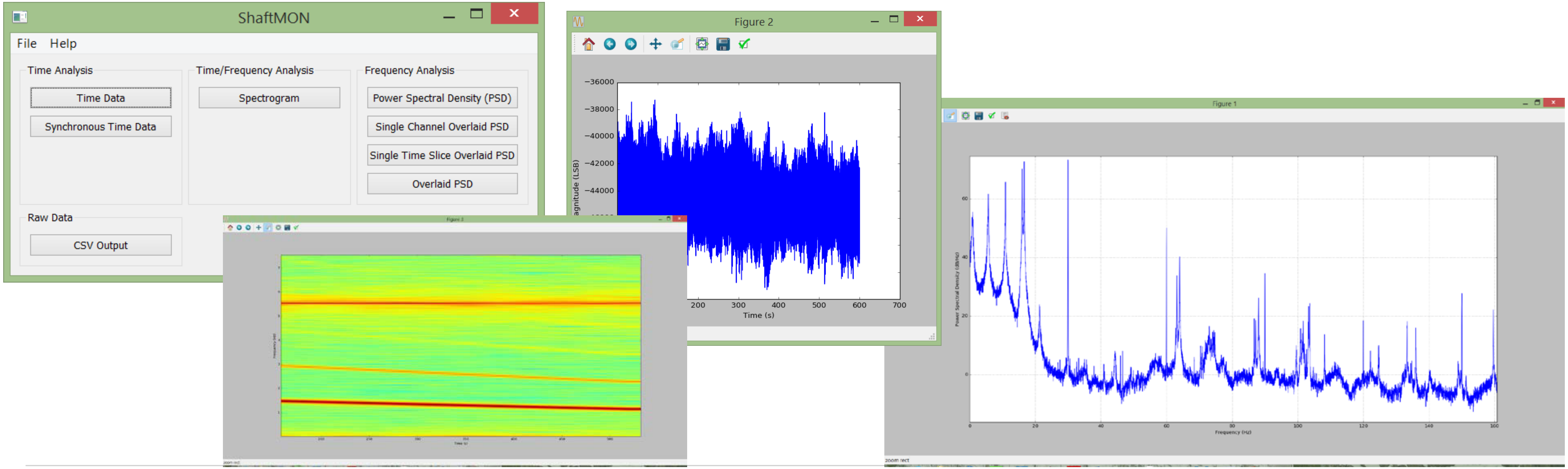
- A mature infrastructure exists to gather the data.

- Not limited to Suprock or EPRI… Can also acquire signals from legacy sensors.
  - Voltage, 4-20mA, etc.

EPRI-Suprock data acquisition interface

Data Post Processing Tool

- Produces various common plots useful for communicating turbine performance.
  - PSD plots of frequency
  - Spectrograms
  - Time data
  - Overlaid spectral data (various sensors or various time windows)



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Next: Real applications and research results.

- Pause for questions about hardware, software, data infrastructure.

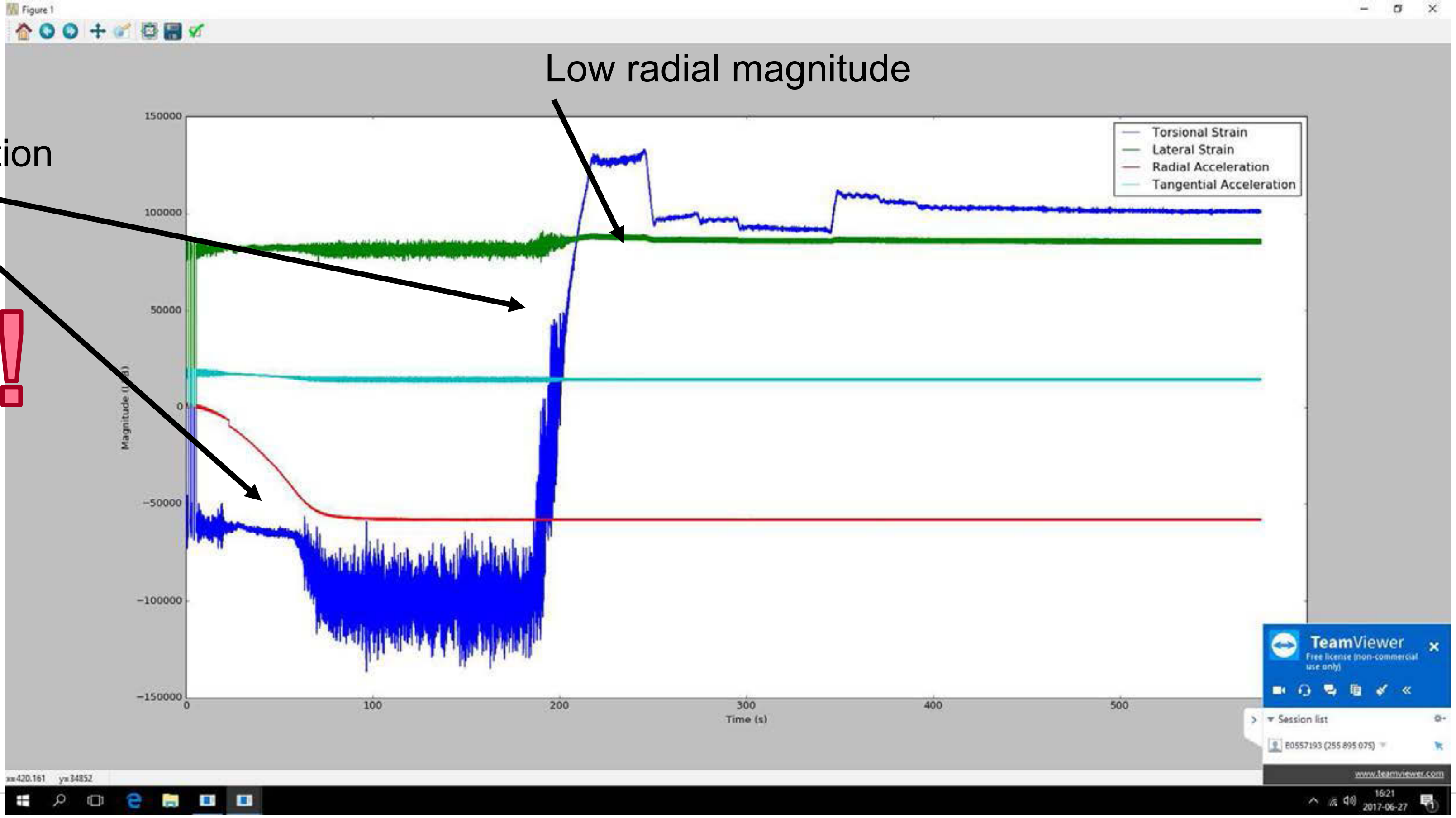
275MW/300RPM hydroelectric Francis turbine-generator

- Torsional vibration from bearing failure and turbine rope cavitation.
- The gates were opening too fast during speed ascension at no load.
- Oscillation is unstable and persists until torsional loading re-estabilishes stability.

~2M ft*lb

torsional oscillation

Yikes!

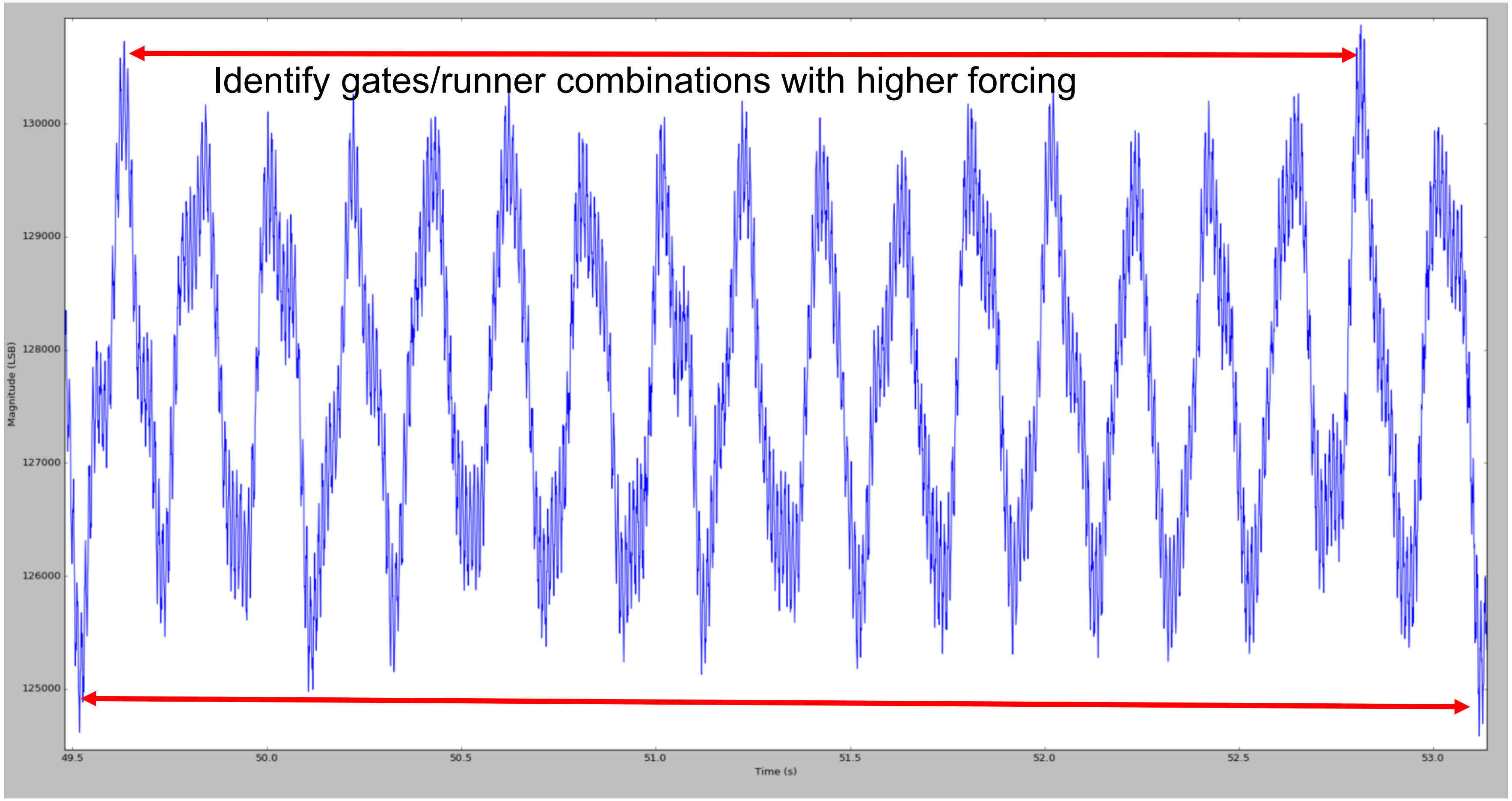


Notice how radial acceleration does not disclose the magnitude of the torsional vibration.

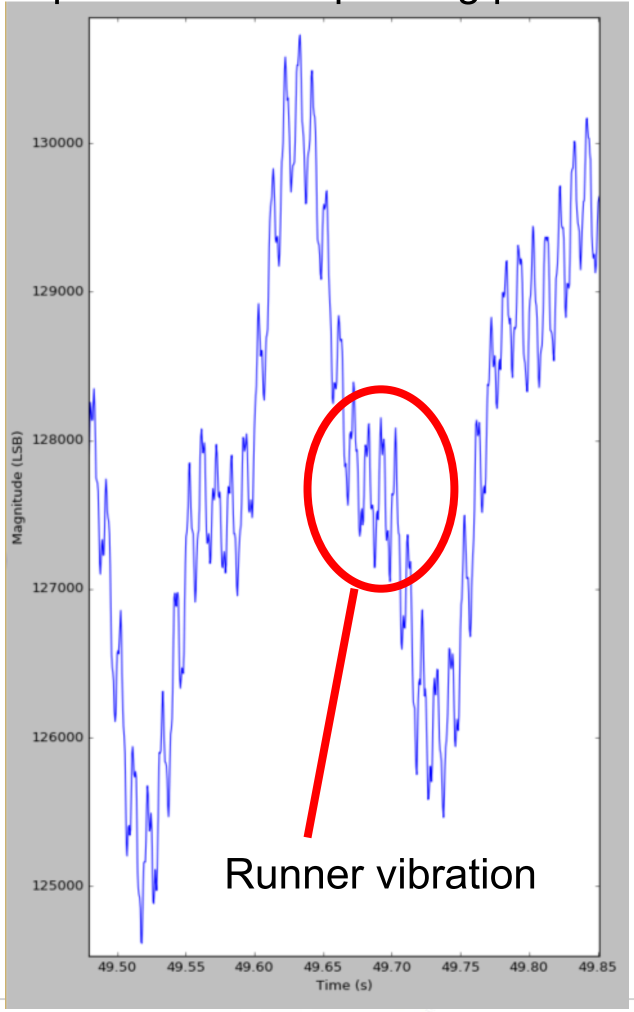
Likewise radial probes are blind to this major vibration.

Resolution of telemetry allows deep inspection

- Inspect periodic features with high resolution, like gate/runner passing magnitudes.
- Each waveform tells a story about the motion of the rotor.



Inspect individual passing periods



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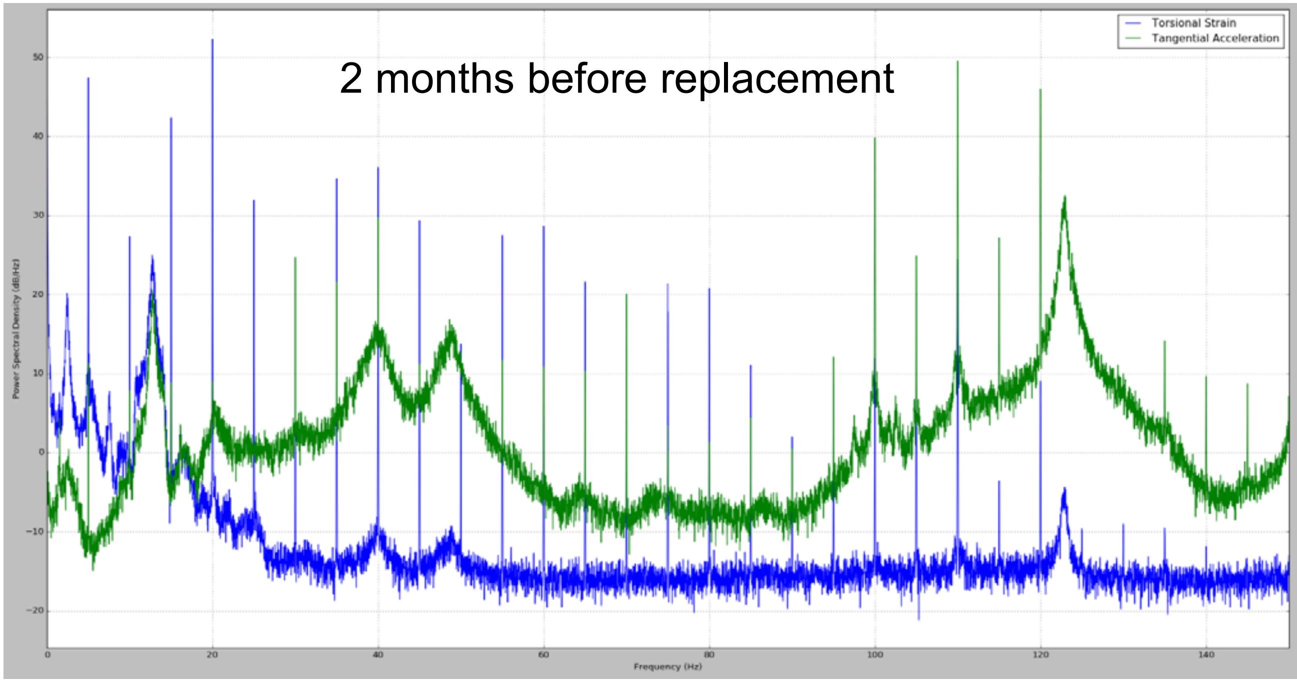
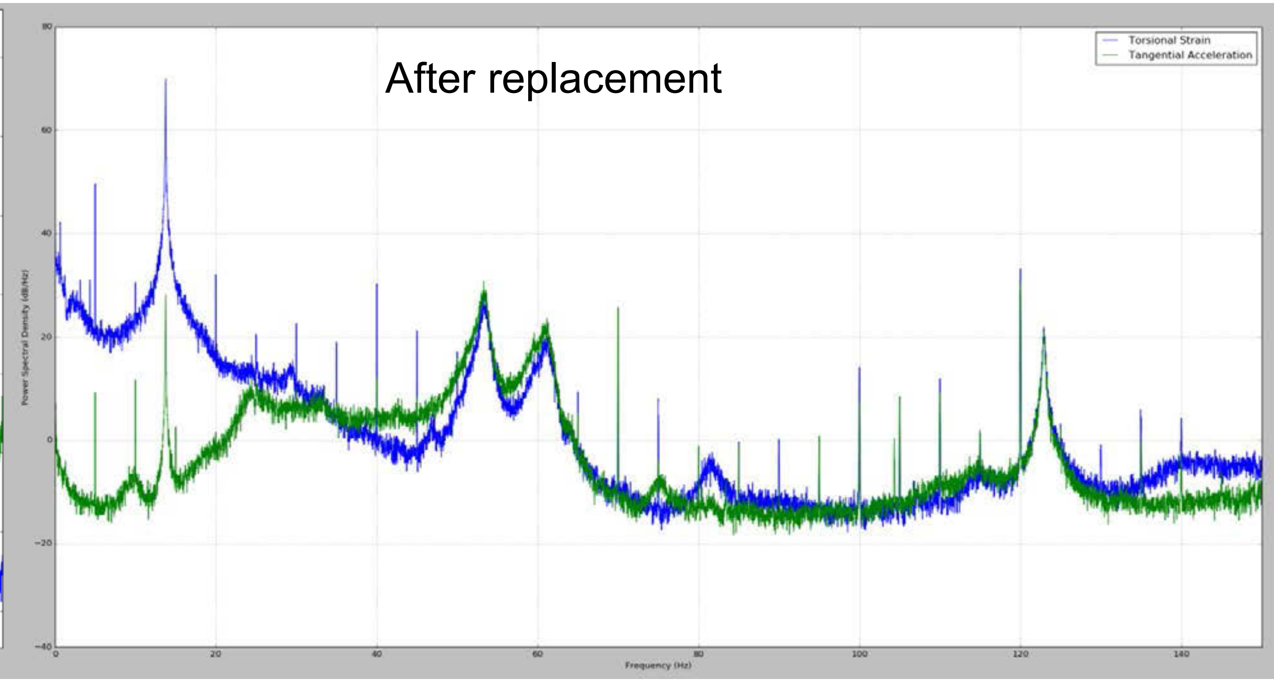
Detecting bearing shoe failure in rotor dynamics

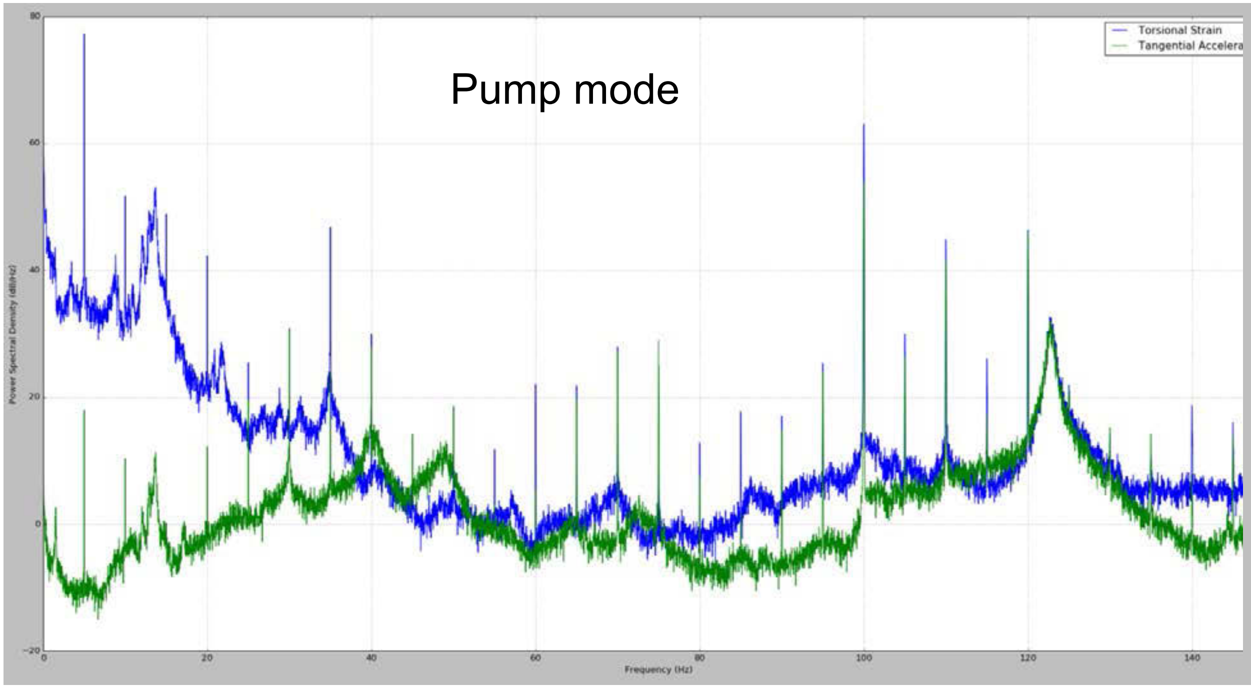
- Utility did not notice significant trend in APR from stationary probes until complete failure of a bearing set screw.
- Major differences in machine dynamics identify an issue with bearing orbit.

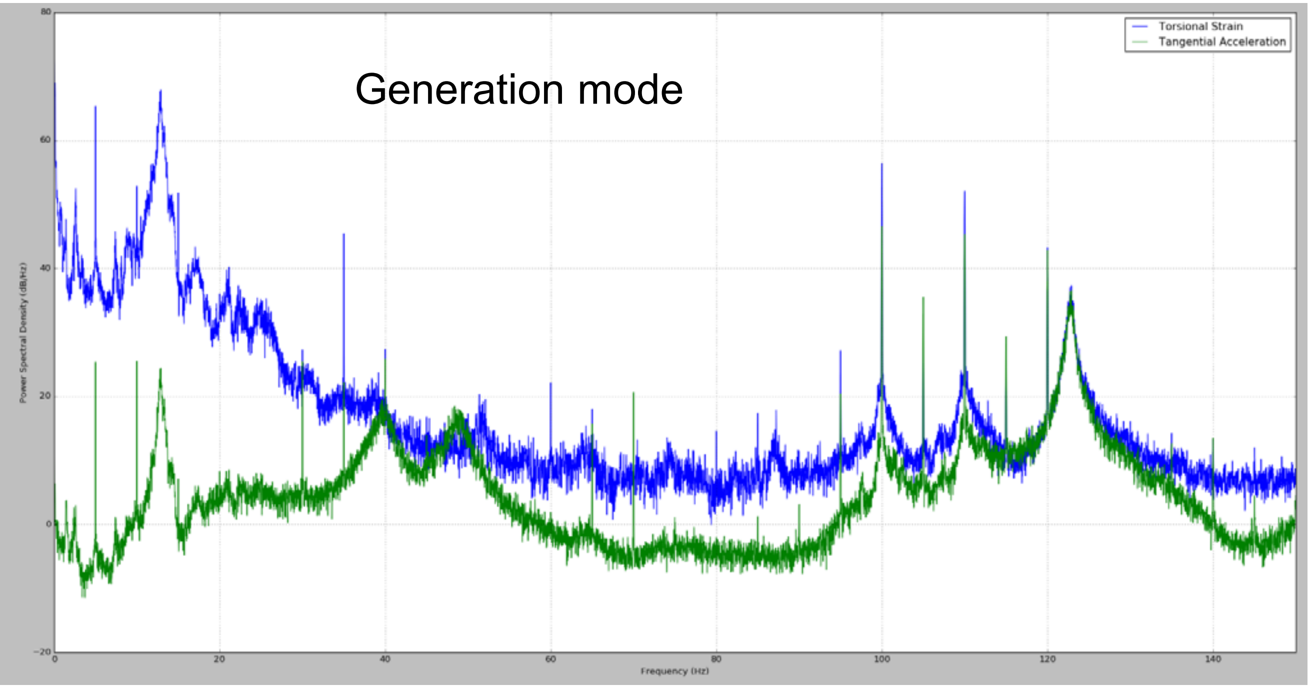




Comparing pump and generation modes in pumped storage

- Behavior differences in driven/vs reactive turbine use.
- Differences due to gate control.
- Gate passing frequency magnitude very different.
- Forced response excites different modes of the unit.
- **Same unit has two different monitoring signatures depending on mode.**





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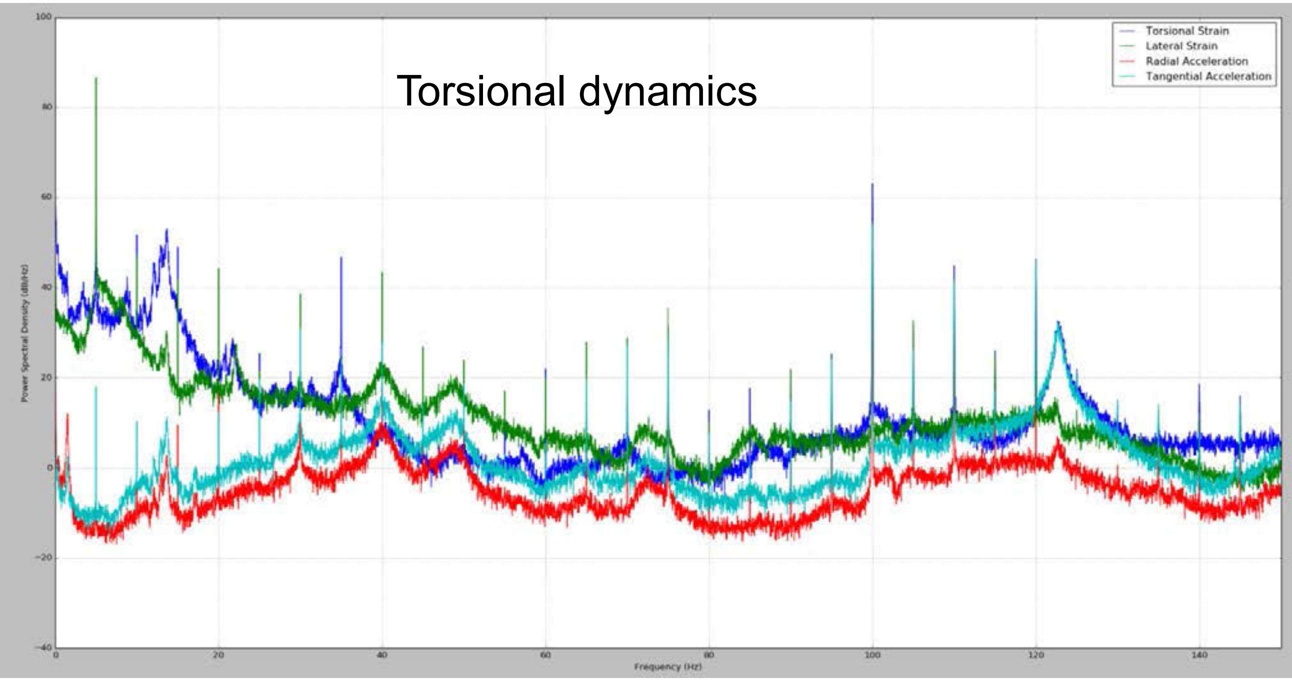
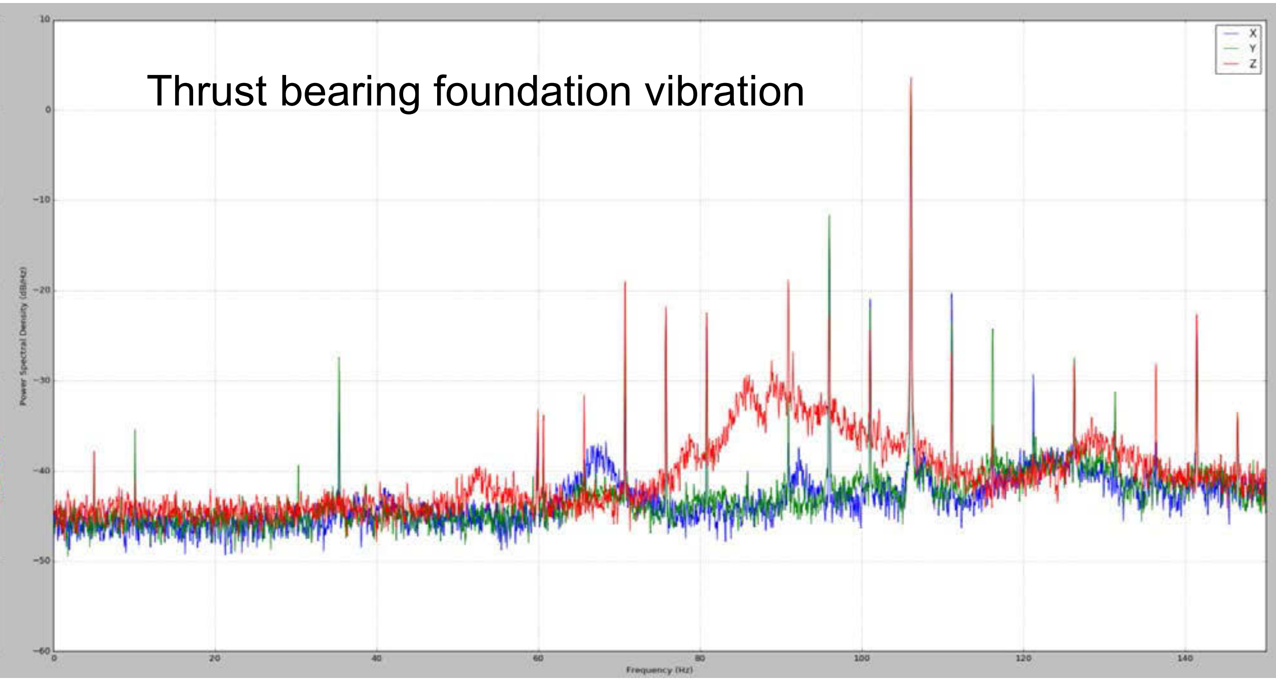
Bearing vibration vs rotor vibration

- Very different sets of information!
- Stationary vibration does not capture torsional behavior.
- Event driven monitoring or pattern recognition should have both sources to predict different types of failures.





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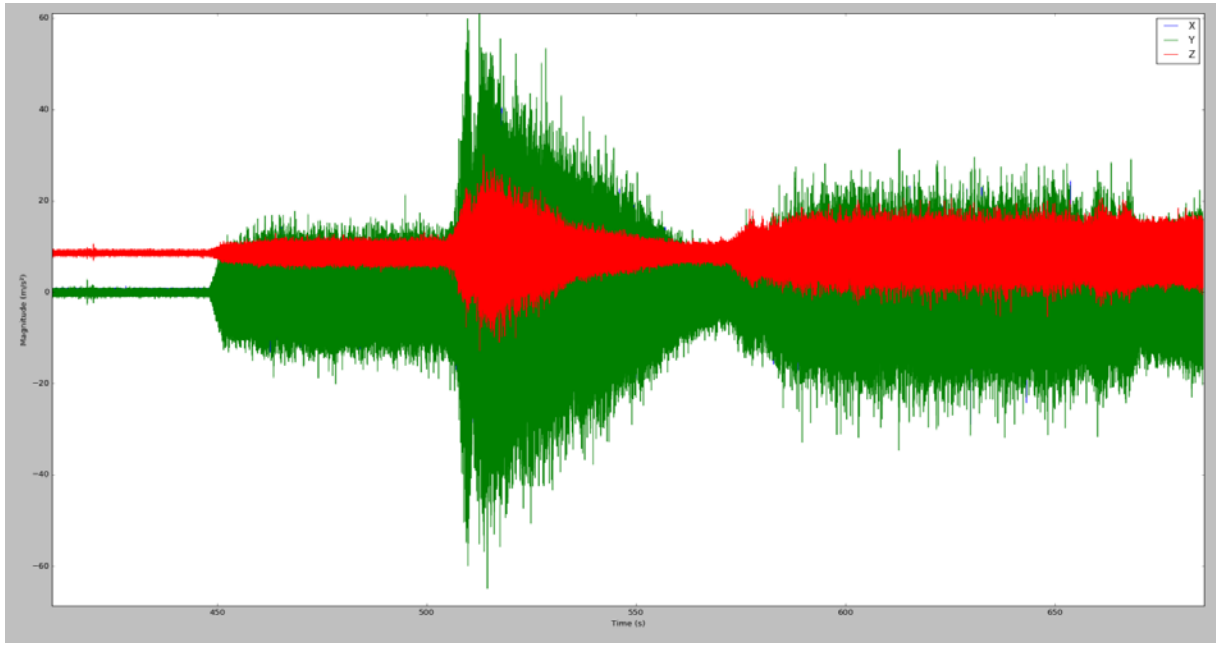
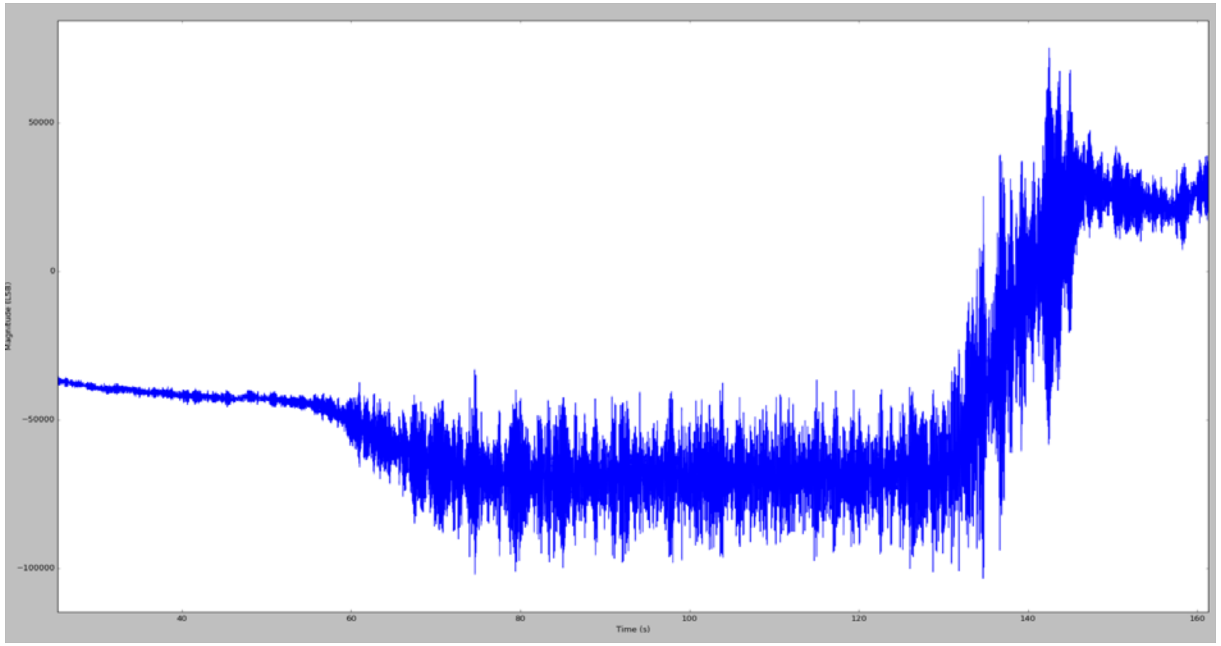
Gate vibration vs torsional vibration

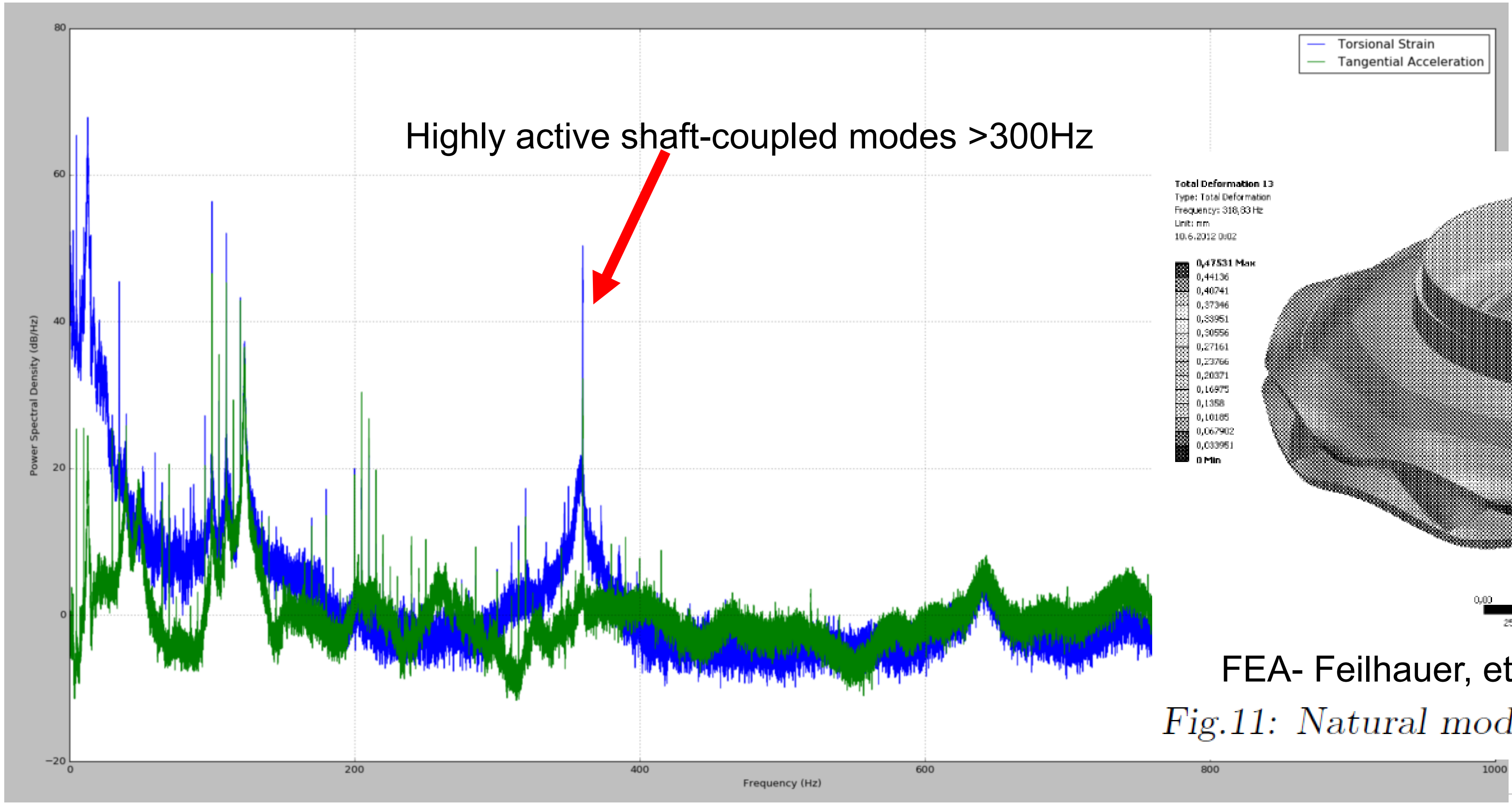
- Next steps include transmissibility between individual gate motion and torsional dynamics.
- Instrumentation of gate drive linkage components with strain gages (especially in ring controlled gates where motion is not independent)

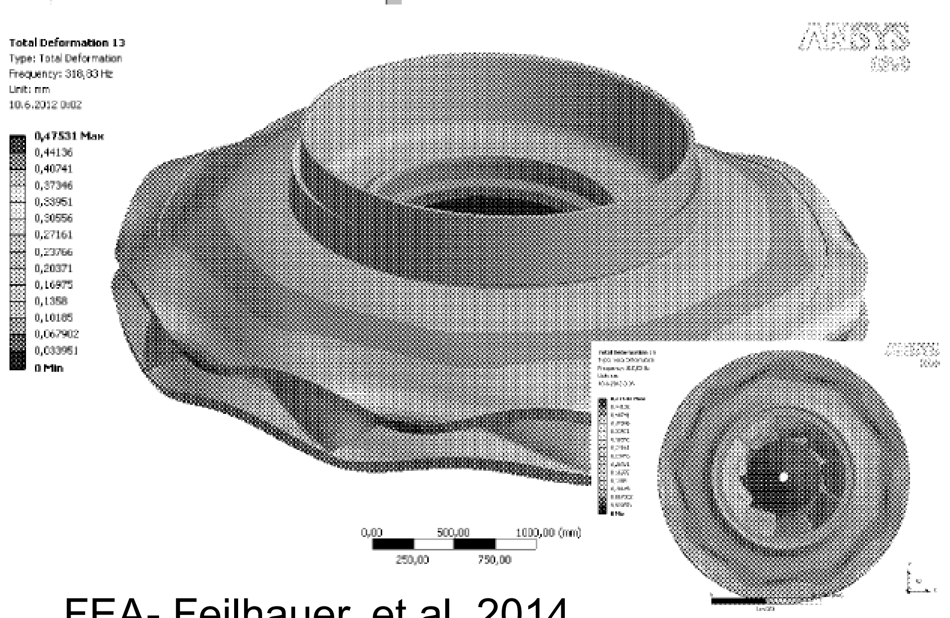




High frequency turbine vibration detection from the shaft location

- Cavitation or higher order modes of the turbine vibration.
- Turbine modes, etc.
- Similar to blade vibration detection in steam turbine-generators.





FEA- Feilhauer, et al. 2014

Fig.11: Natural mode shape – $f_{13} = 318.833$ *Hz*

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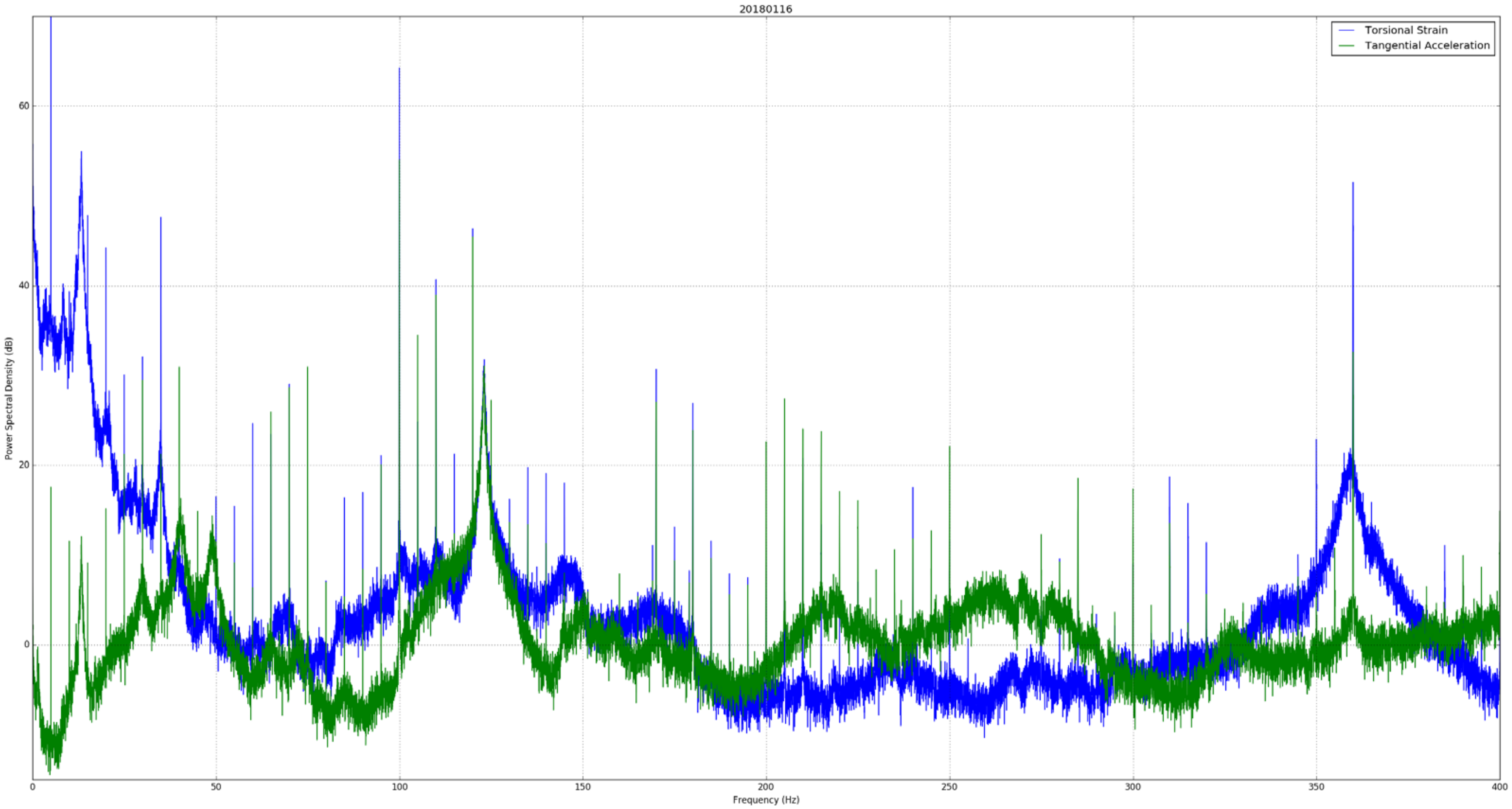
Trending long term changes in rotor dynamics

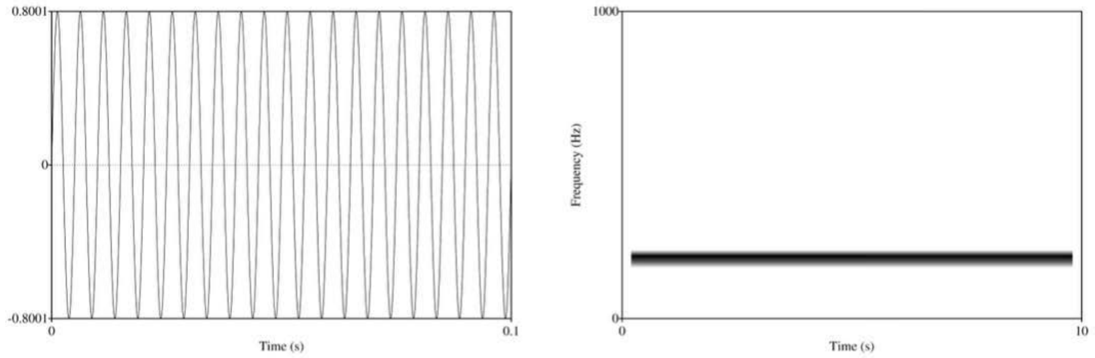


Brief introduction to time-frequency "Spectrograms"

Operational deflection is not just a static parameter at different MW values. Operational deflection happens across a wide bandwidth of frequency.

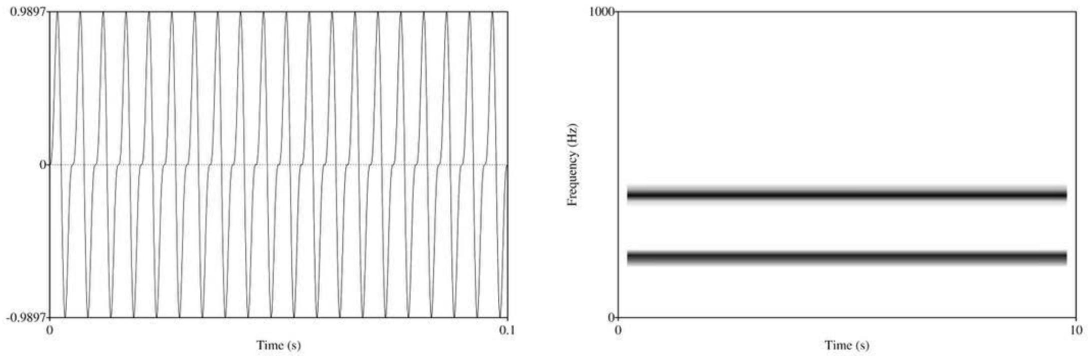
Distinction Between Waveforms and Spectrograms

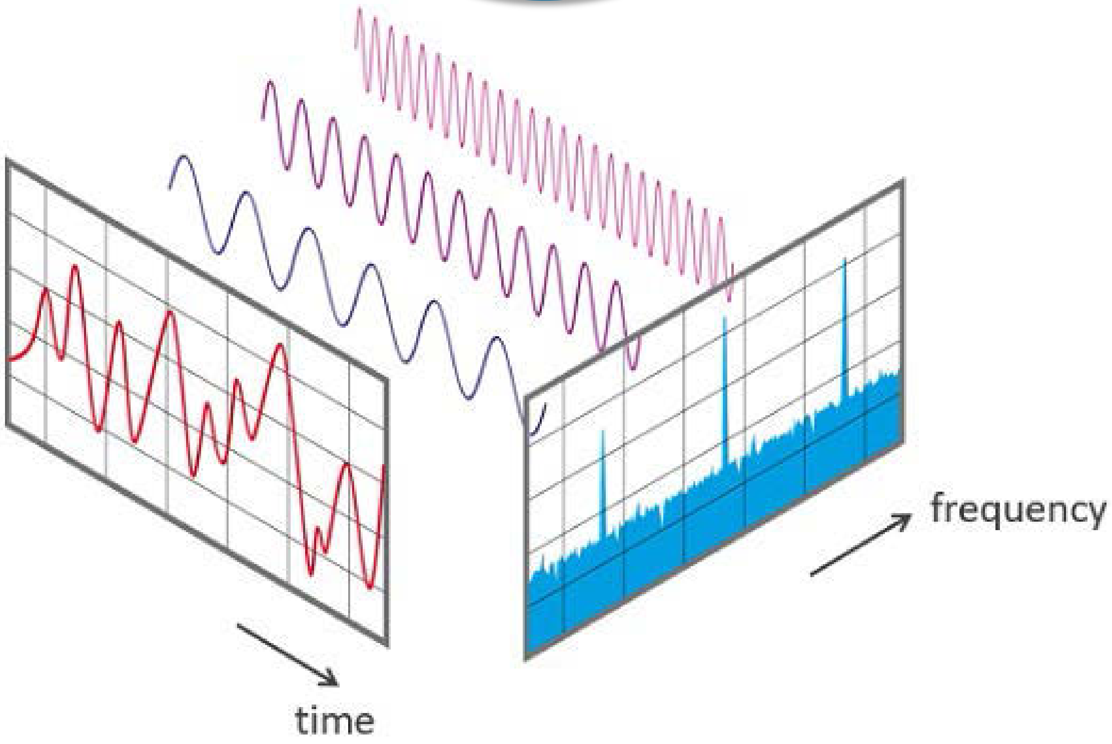
Waveform (left) and spectrogram (right) of 200Hz sine wave



Complex Wave with 200Hz and 400Hz Components

Components have same amplitude





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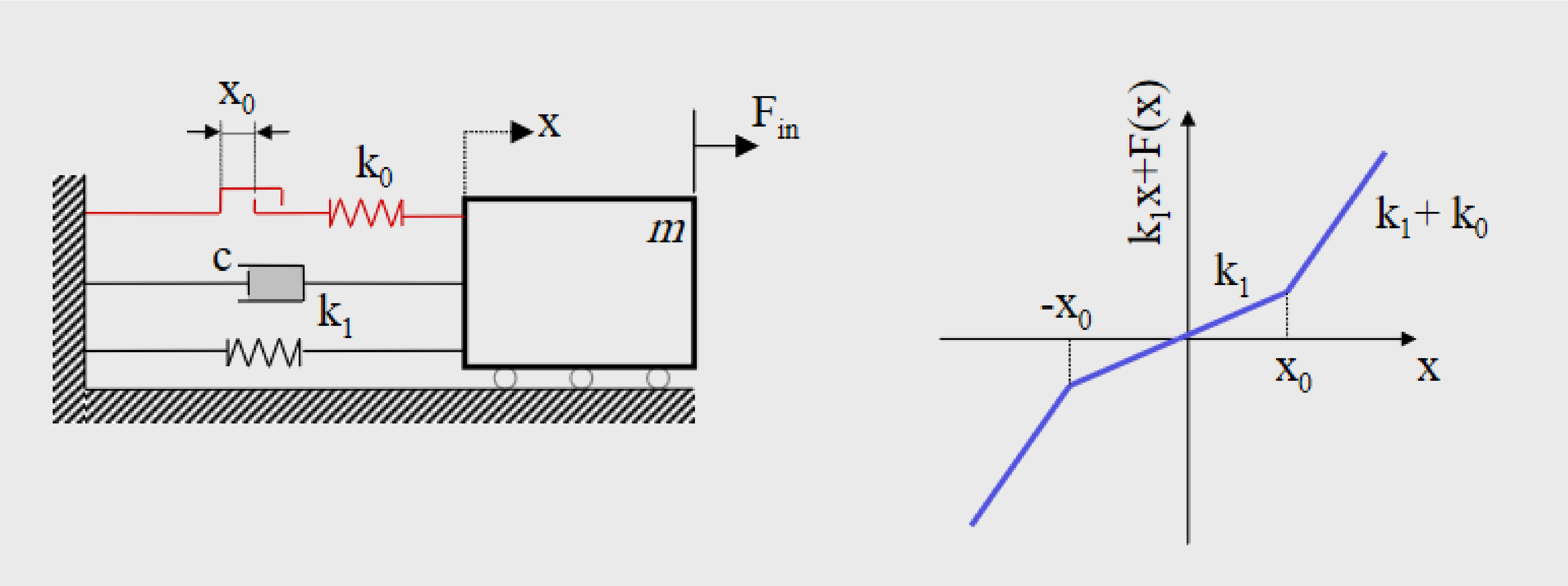
Nonlinear stiffness (backlash parameters)

- In an ideal elastic system, everything should be nice and linear.
- In a system with cracks or discontinuities, there is a backlash element in movement.



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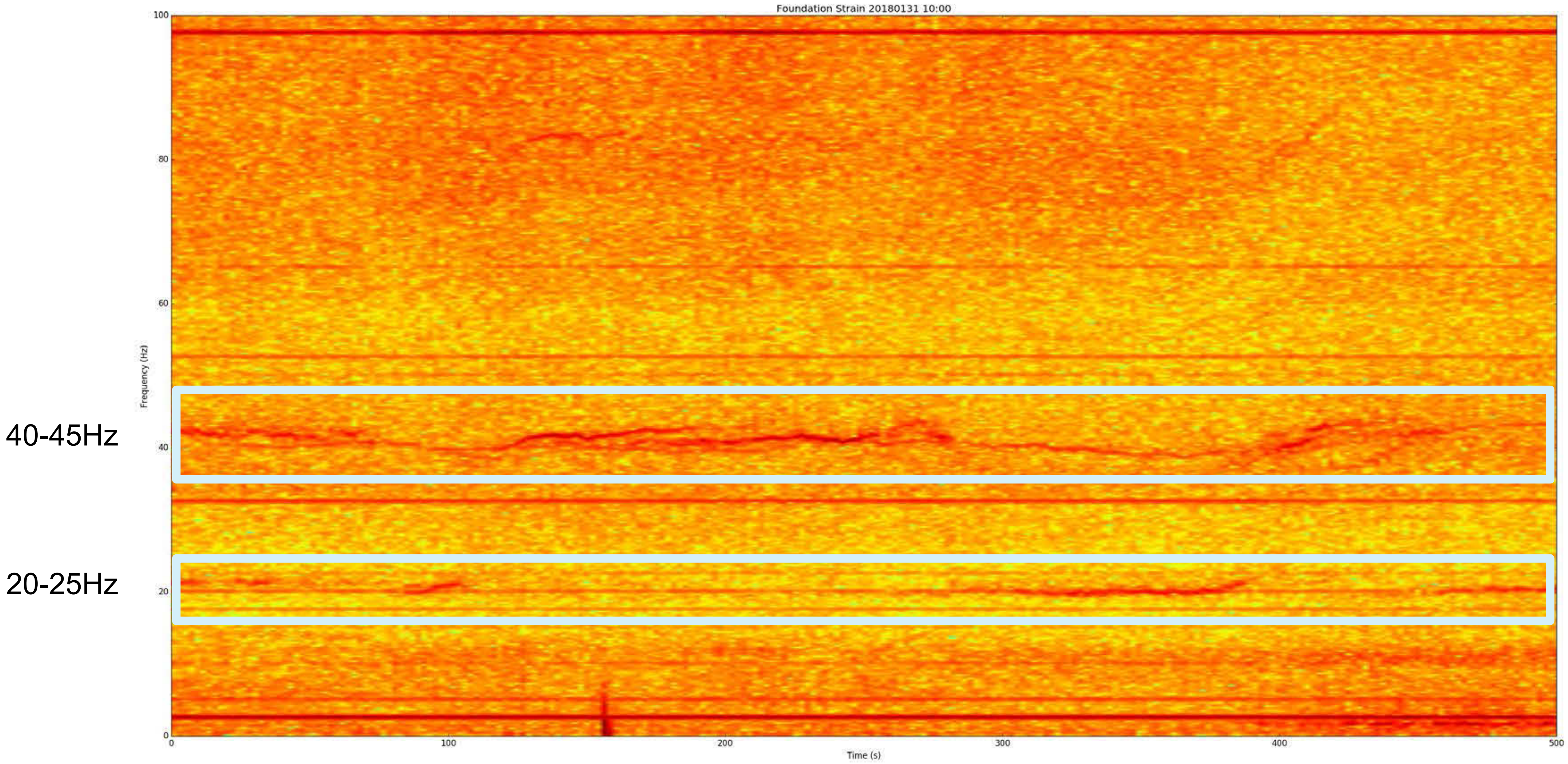
Identifying non-linear frequencies related to foundation cracks.



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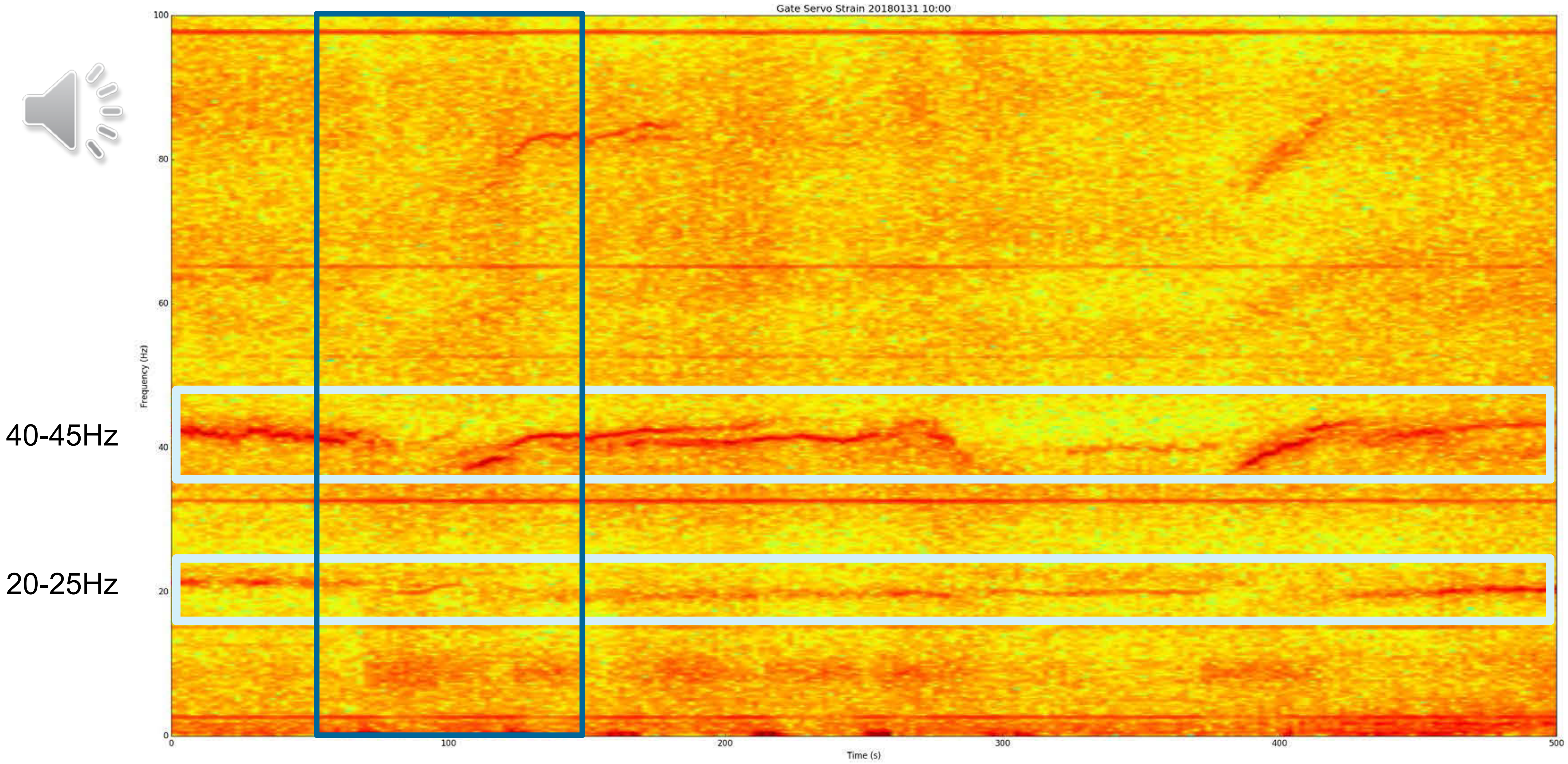
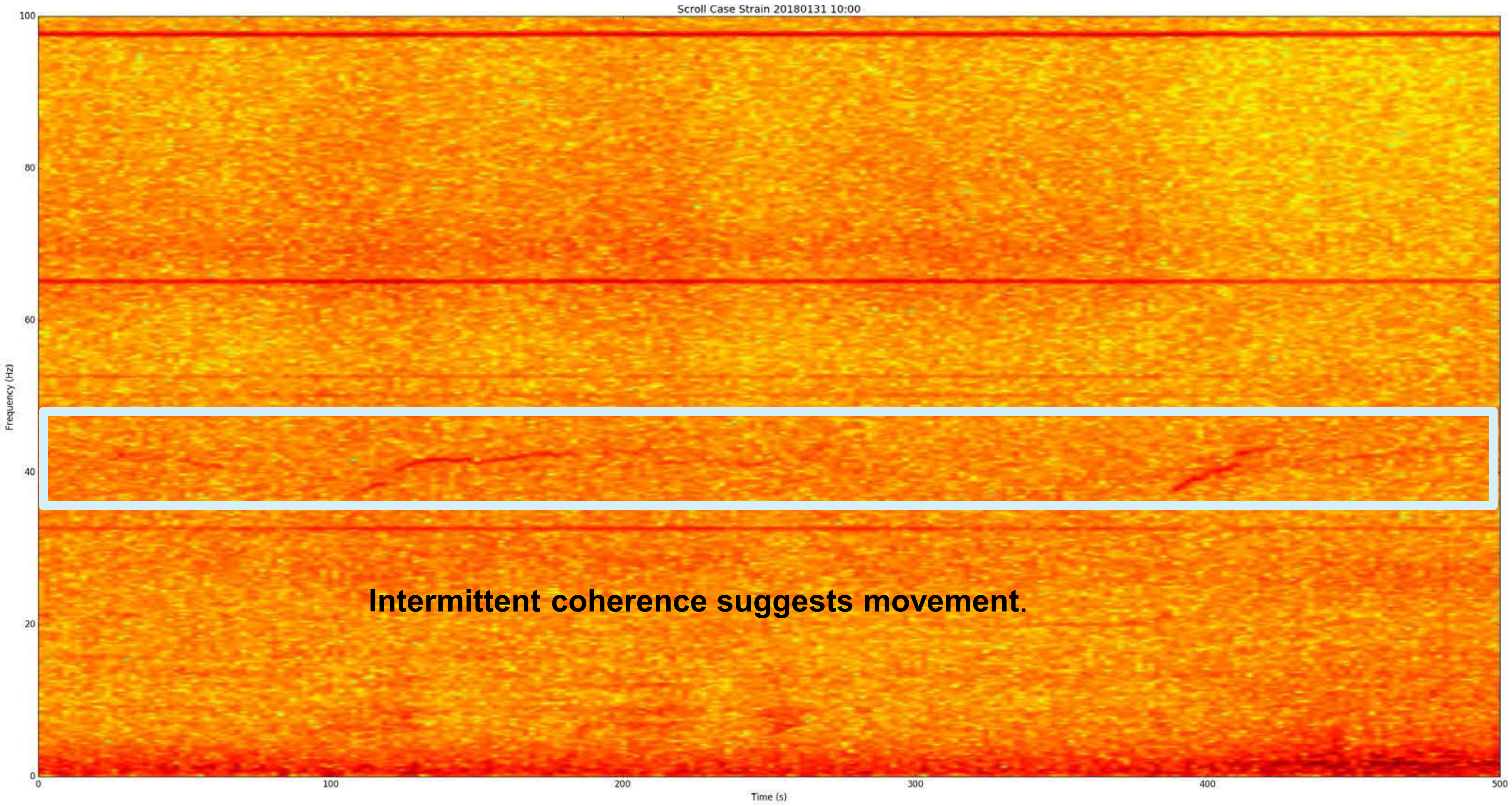


Identifying non-linear frequencies related to foundation cracks.

40-45Hz

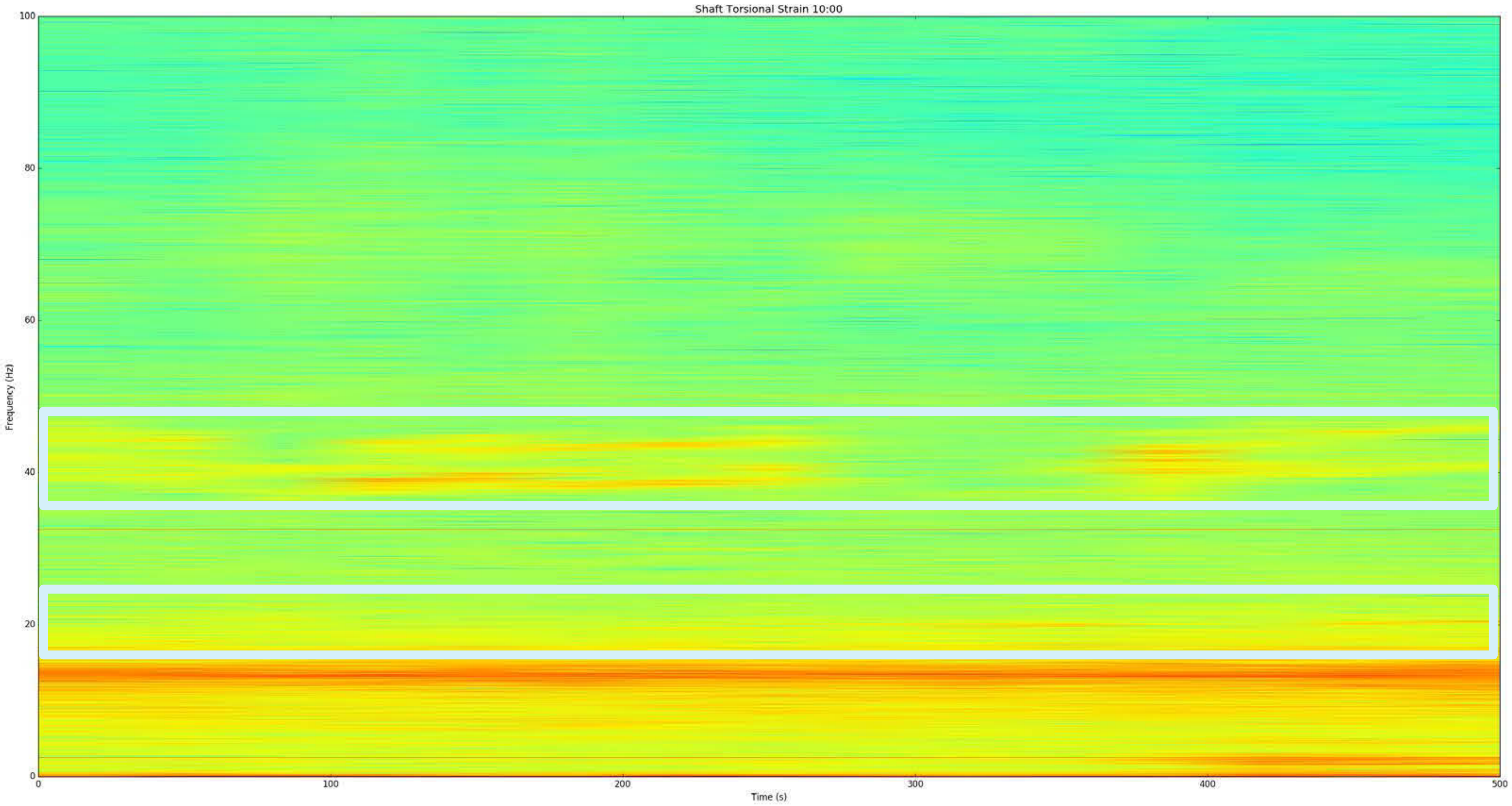


Intermittent coherence suggests movement.

Identifying non-linear frequencies related to foundation cracks.

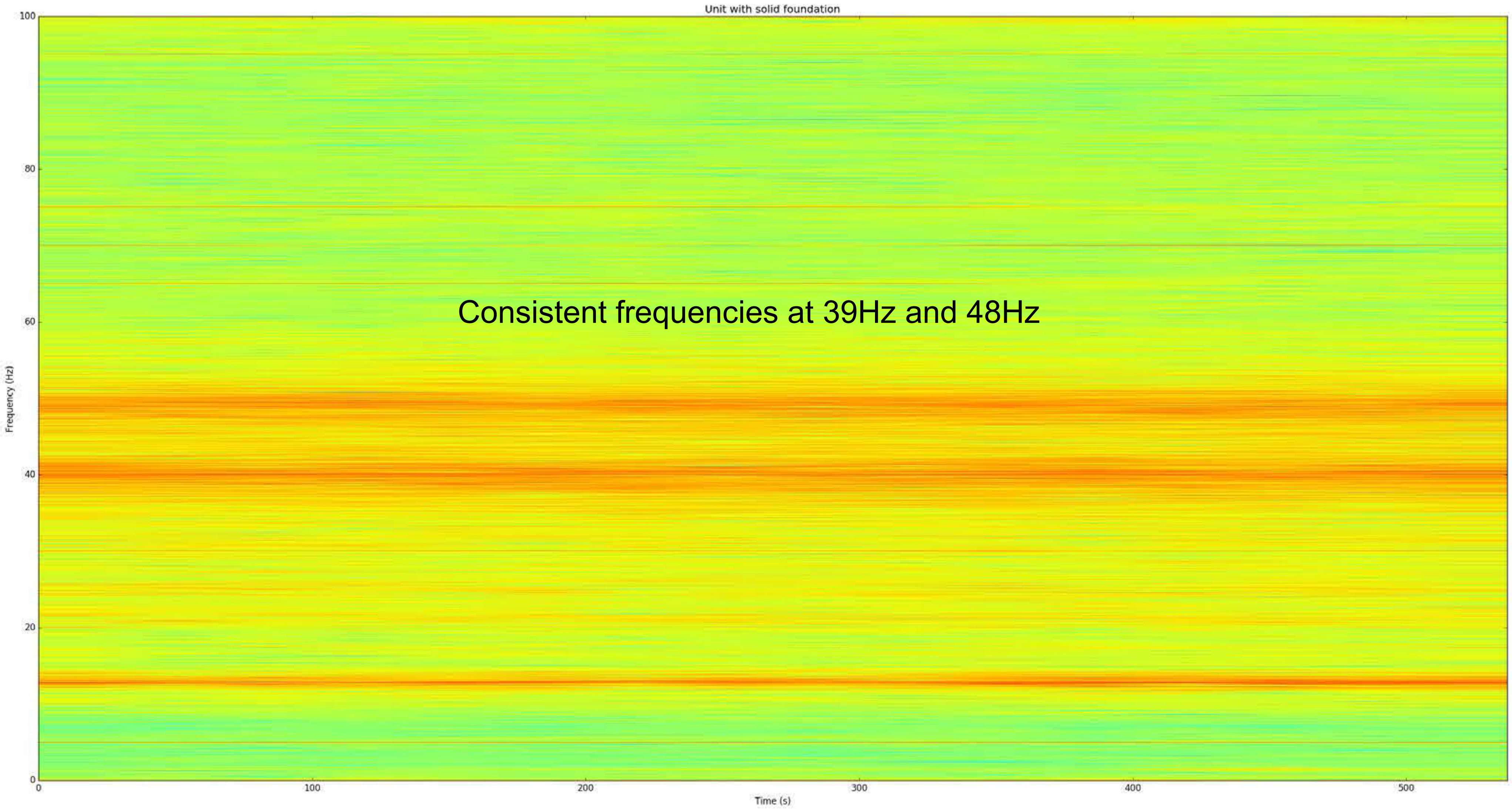
40-45Hz

20-25Hz



What does a “solid” foundation do?

Different unit, with similar mechanical arrangement.



Correlation of multiple dynamic sensors can:

- Capture the unique movement of each power unit.
- Quantify differences in observed deflection and vibration between sister units.
- Evaluate if there are any implications related to motion of the power unit to the maintenance plan.
- Operational deflection of the unit can be a monitoring parameter.
  - Know if the unit changes stiffness, position, or vibration characteristics.
- **Frequency tracking analyzers can alert operators if there are developing changes in the normal movement of the unit.**

Completing the monitoring vision

- Connecting to SCADA, DCS, APR, etc.

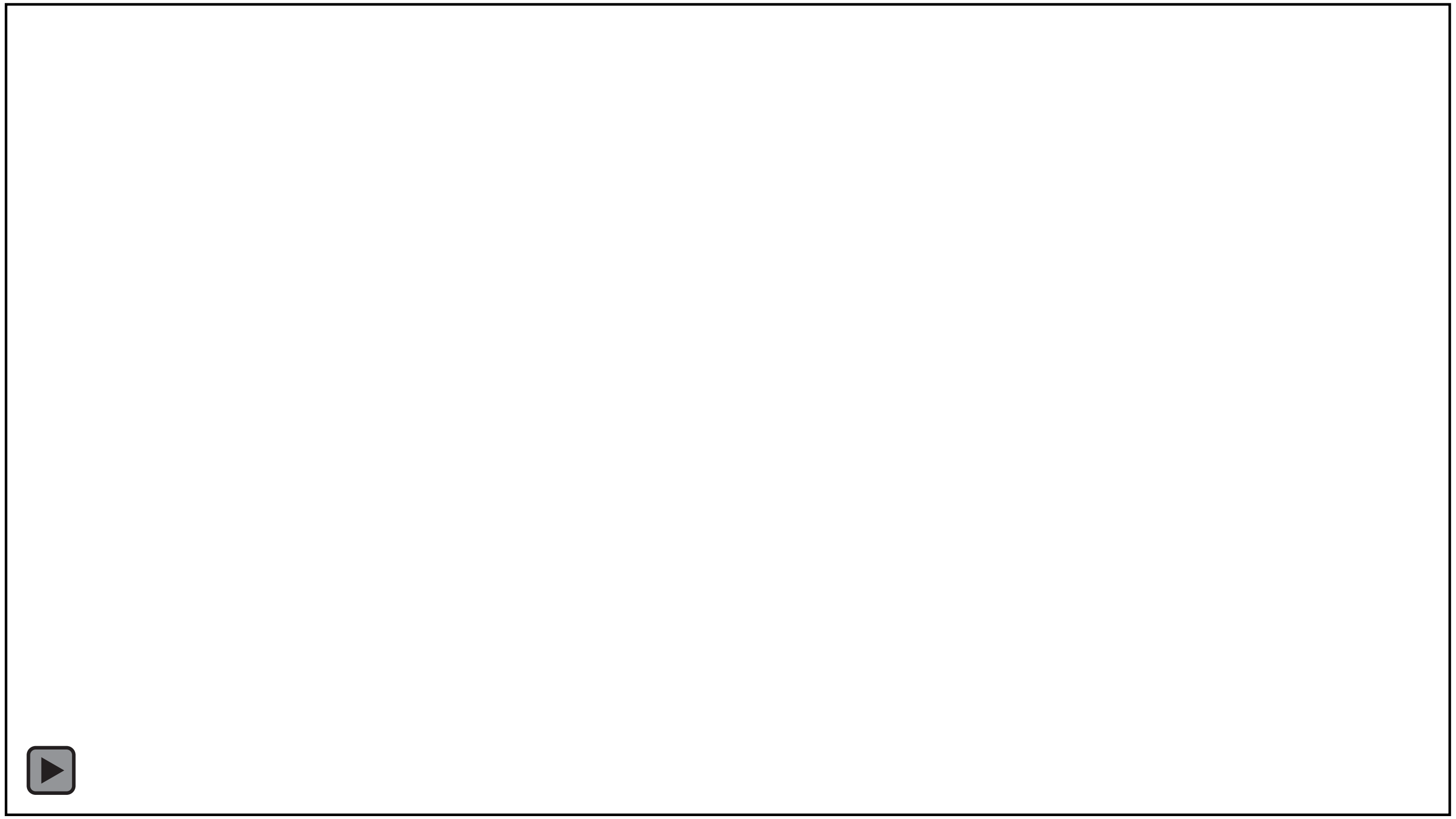
- Implementing analysis of frequency, magnitude, and alarm limits based on these new sources of data.

- Leveraging proven fast data analytical packages.

- Avoid burdens to legacy plant systems.
  - Provide information results at a rate and form that is acceptable to plant systems in-place.

Unit-local APR handles fast data

- Produce data results to feed legacy APR or SCADA systems.
- An application built on top of the software infrastructure discussed.
- Proven analyzer technology monitoring high value manufacturing assets.



Reporting of data reduction

- Massive amounts of data are turned into valuable information.
- High speed data can be preserved during events of note. (before & after a fault)
- Example data reduction summarizing measurement point:

Spindle Analysis Results		
Parameter Type	Result	Description
Bearing Result	Satisfactory Fault Stage 1	Good condition
Vibration Result	Other Vibration Alert	Needs immediate attention

Spindle Analysis Parameters	
Parameter Type	Value
Acceleration RMS	0.217984 g's
Highpass Acceleration RMS	0.003098 g's
Velocity RMS	0.149795 ips
Sampling Frequency	62500.000000 hz
TWF Peak	1.590326 g's
Crest Factor	7.295616

This is the type of result information a plant system can receive without issues about the data rate or complex analytics.

Ongoing applications with hydro monitoring

- Explore shaft-coupled mode sensing of both turbine and generator.
  - Work with OEM or hydro turbine design engineers at plant sites experiencing issues with turbine vibration.
- Placement of similar sensors inside the generator on bus bars, spiders, ledges, etc.
  - Temperature, strain, acceleration.
- Completing the monitoring needs by closing the loop to the plant data system.
- Auxiliary asset monitoring using wireless sensors and leveraging the same infrastructure to add this information to the plant data system.

Ongoing and future applications of TDMS

- EPRI research exploring additional applications to power generation equipment:
  - Hydroelectric turbine-generator sets
  - Combustion turbine-generator sets
  - Turbine/compressor blade vibration detection
  - Continuous shaft health monitoring
  - Health/tuning of generator controls

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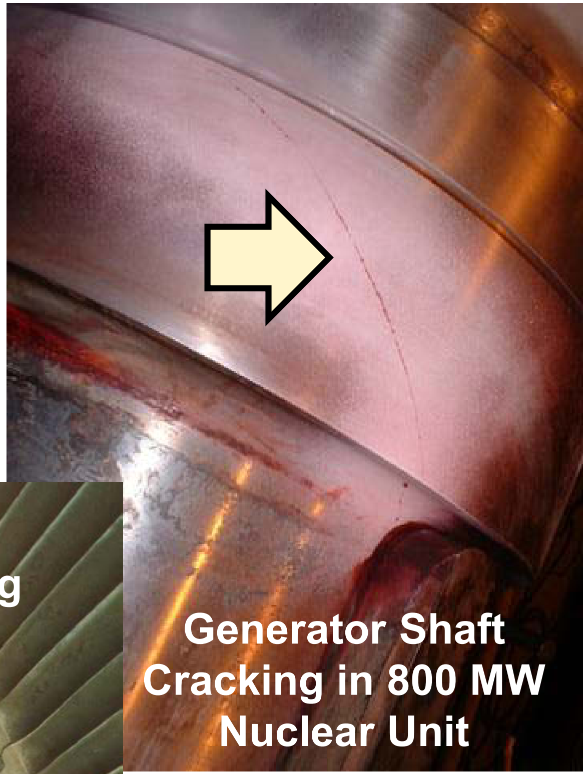
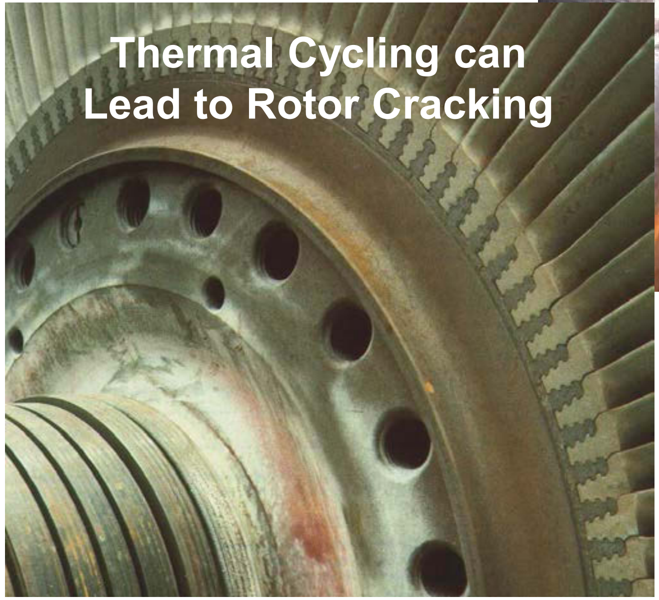
Future Applications of Shaft Vibration Sensing

- Turbine-Generator shaft health degradation monitoring
  - Turbine-generator rotor/shaft cracking is infrequent, but has high consequences if undetected
  - Proposed concept for TDMS application:
    - Monitor/trend shaft natural frequencies (torsional and lateral)
    - Use feature extraction; apply *Advanced Pattern Recognition* (APR) to highlight anomalous trends
    - Companion FEA necessary…provides basis for action levels





Questions and Discussion….

Together…Shaping the Future of Electricity