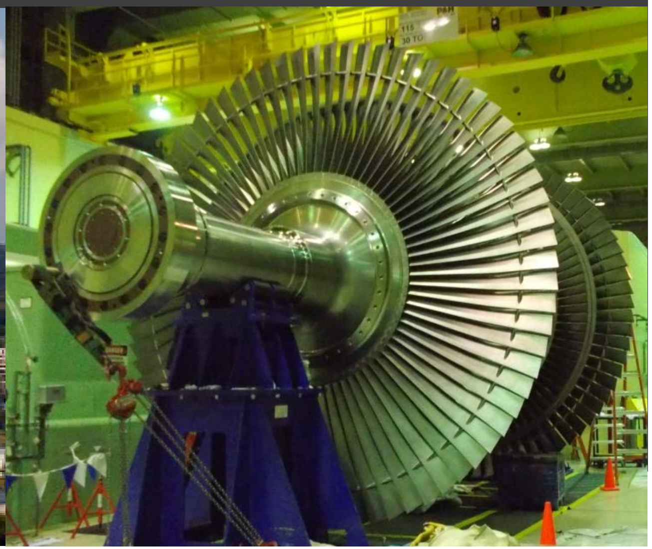
SUPROCK TECHNOLOGIES

MPR

Turbine Generator Crack Monitoring: Feasibility and scope

Chris Suprock, PhD - Suprock Technologies
Kevin Myers, P.E. - MPR Associates



Outline

- Introduction
- Summary of Issue
- Potential methods for online cracked shaft detection
- Steps Required for Implementation
- Application of TDMS
- Challenges
- Conclusion

Suprock Technologies

- Developed Turbine Dynamics Monitoring System (TDMS) under EPRI Program 65 funded initiative
- Specialization in advanced sensor technology and machine monitoring

MPR Associates

- Has supported the power generation industry since 1964
- Modeled, tested and/or analyzed >100 rotor trains with respect to torsional vibration issues

Teaming approach to modeling, analysis, and physical measurements

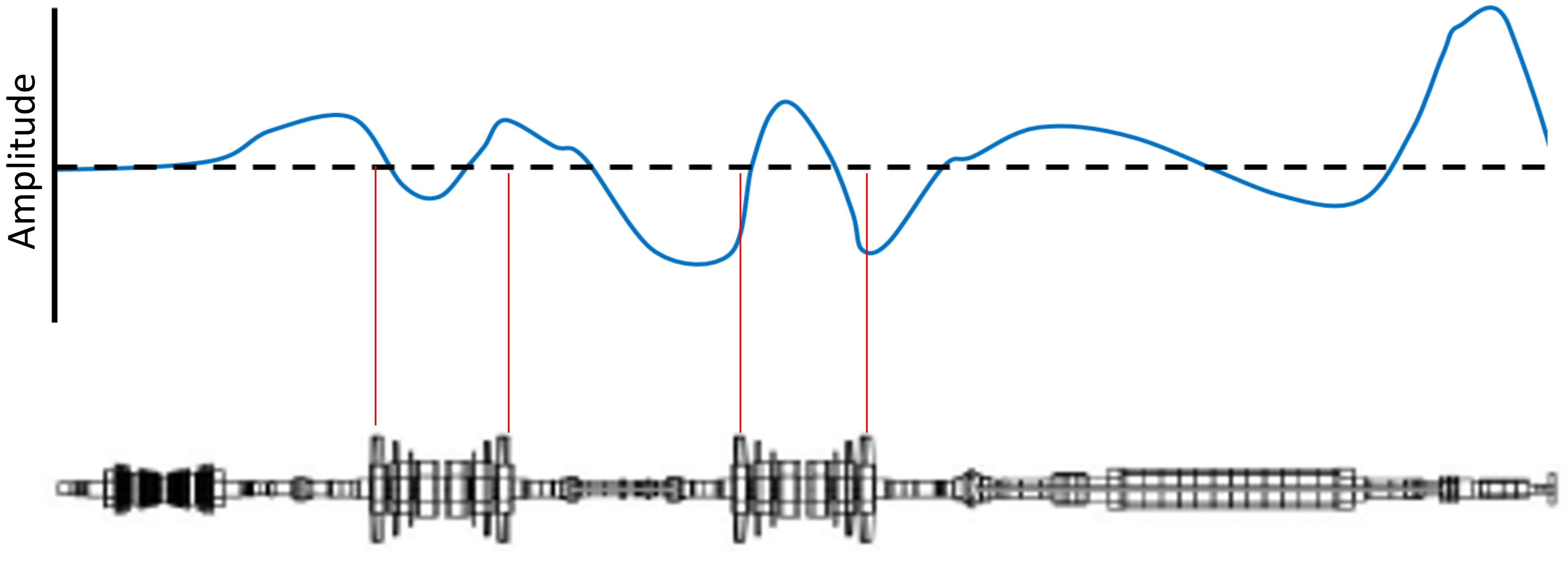
Turbine-Generator Rotor Cracking – Issue Summary

- Shaft cracks leading to catastrophic failure are rare, but extremely dangerous and costly if they do occur
- Inspection and replacement intervals are being extended due to increasing economic pressures, thereby increasing the potential for an undetected crack to grow beyond the critical crack size
- Online monitoring for shaft cracks may be desired in cases where a unit has a known susceptibility. Examples include:
  - Age of unit is beyond fleet operating experience
  - Cracks previously discovered on a specific rotor train or rotor train of similar design/vintage

Effect of Crack on Shaftline Rotordynamic Response

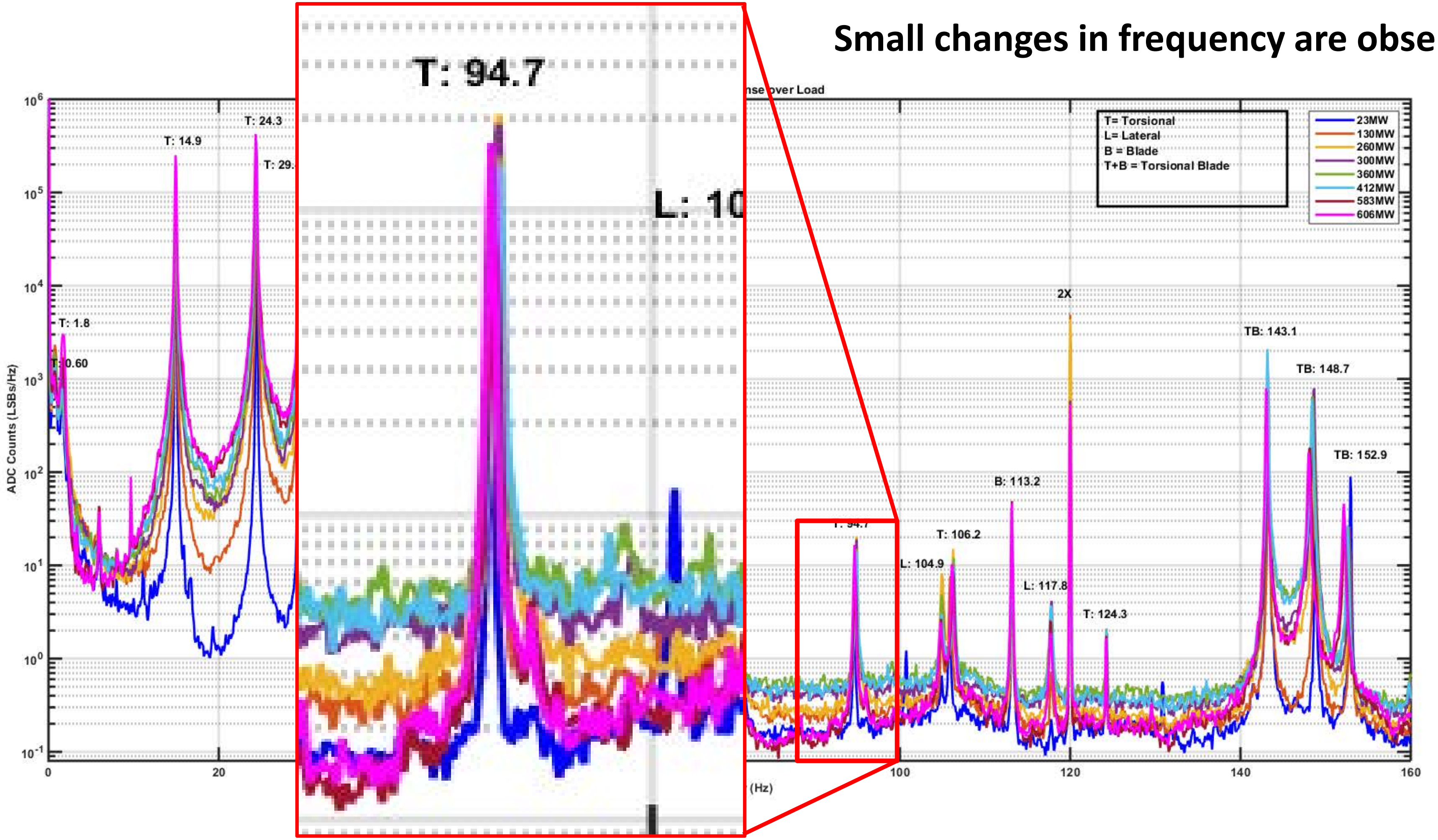
- As a crack progresses through the shaft, the stiffness of the shaft will be reduced
- **The reduced stiffness will decrease the natural frequencies of the rotor train**
- The extent of the frequency shifts will vary from mode to mode, depending on the mode shape and shaft participation (bending/twisting) that occurs at the crack location
- The magnitude of vibrations in response to a given excitation input may also vary

Example Mode Shape – Defined by rotor stiffness and mass



Example torsional spectrum

Small changes in frequency are observable



Conceptual Feasibility Evaluation –Torsional Vibration Approach

- Detecting cracks in turbomachinery via changes in torsional natural frequencies has been investigated and test previously by other
  - Primarily on small test shafts, supplemented with theoretical analysis for larger shafts
  - MPR is not aware of this type of system being used in the field for online crack detection monitoring of large turbine-generators

- Torsional mode frequency shifts expected to exceed 0.1 to 0.2 Hz by the time cracks exceed 20% of the rotor cross-section
  - Failure of shaft is not expected until cracks progress much further (historically failures occur after shaft crack has propagated 1/3 to 1/2 (or more) of the way through the shaft
  - State-of-the-art torsional vibration monitoring systems are capable of discerning frequencies at a resolution more than an order of magnitude less than 0.1 Hz
  - A shift of 0.1 to 0.2 Hz is therefore easily detectable and differentiated from other potential non-crack variables.

Steps Required for Implementation

- Site-specific feasibility study
  - Confirm critical crack size is greater than detection capability
  - Confirm crack growth rate is expected to be slow enough to allow action after detection (adequate margin between detection threshold and expected failure point)
  - Determine optimized implementation strategy
    - Number of units
    - Available windows for instrument installation/baseline measurements
    - Sequencing of analysis effort with site measurements

Steps Required for Implementation

- Modeling and Analysis
  - Determination of likely crack locations and crack propagation morphology/path (radial versus torsional)
    - Informed by experience and stress analyses
  - Correlation of crack size versus rotor stiffness
    - Stress analysis (FEA)
    - Empirical relationships available from literature
  - Correlation of rotor stiffness change (and therefore crack size) versus torsional natural frequency shifts
    - Baseline model should be tuned/validated against baseline site measurements
  - Determination of crack growth rate and critical crack size
    - Fracture mechanics evaluation
    - Requires shaft material properties that may not be readily available (e.g., Charpy values)

Steps Required for Implementation

- Initial Baseline Measurement
  - Instrumentation installation requires the unit be shutdown. Can be completed in less than one shift once unit is cooled and off turning gear.
  - Ideally performed when it is known that no shaft cracks exist (or there size and location are fully known)
- Monitoring
  - Determine strategy
    - Periodic manual review (if crack growth rate is expected to be sufficiently slow)
    - **Automated/continuous data evaluation with alarms**
  - Establish limits which bound analysis cases
  - Initial data evaluation and monitoring is expected to lead to a refinement of monitoring limits

Application of TDMS to Online Crack Detection

- Torsional natural frequency resolution is sufficient (<0.01 Hz)
- TDMS system is capable of long-term operation
  - No known time-based degradation modes
  - Induced power supply (no batteries)
  - System has hardware self-tests that can be performed via remote internet connection
  - Periodic maintenance checks during planned outage may be recommended
- **Frequency tracking software exists and is compatible with the TDMS.**
- Temperature information collected by the TDMS sensors would aid in adjusting for temperature effects.
- Lateral vibration data collected by the TDMS may be able to be used as a secondary check if torsional vibration data indicates a likely crack

Challenges with Implementation

- Significant analyses work may be required
  - Depends on stress analysis that may already be available from OEM
  - Number of analysis cases geometrically increase as multiple crack locations and crack propagation directions (radial vs. circumferential) are considered
- Availability of rotor dimensional and material information needed for analysis
- Crack growth rates and fracture mechanics analyses tend to have large uncertainty ranges. Therefore, it is recommended that the system be used for crack detection, not crack growth monitoring
  - System would be expected to provide early indication to allow for planned safe shutdown
  - Continuing to operate with a known crack for an extended period of time is not recommended. With enough experience/data gathered on a specific rotor it may be possible at some point in the future.

Modeling Summary

- Identifying mode shapes and their participation in the area of a crack.
  - Specifically watching for **changes in frequency that denote changes in stiffness** participation from the rotor train.
  - **Estimate actionable frequency changes related to crack growth**

- Physical monitoring
  - Watch for relevant **changes in frequency associated with growth of cracks.**
  - Multiple sensor types observe all the torsional modes from one location.

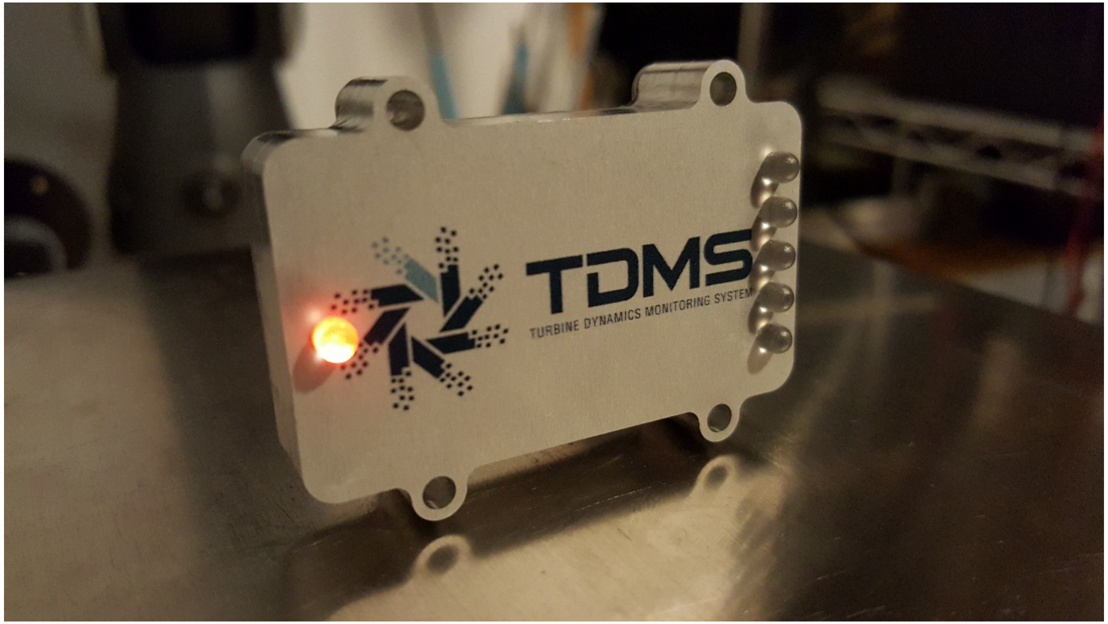
EPRI developed TDMS

TDMS
TURBINE DYNAMICS MONITORING SYSTEM

- TDMS- *Turbine Dynamics Monitoring System*
- Patent and commercial license through EPRI.

- **EPRI response to industry need for torsional testing.**
  - Simple engineering documentation.
  - Rapid response time to test requests (days, not months or years).
  - Multi-dynamics telemetry increases test confidence.
  - Capable of long term operation during extended startups and/or monitoring.

TDMS Quad Telemetry

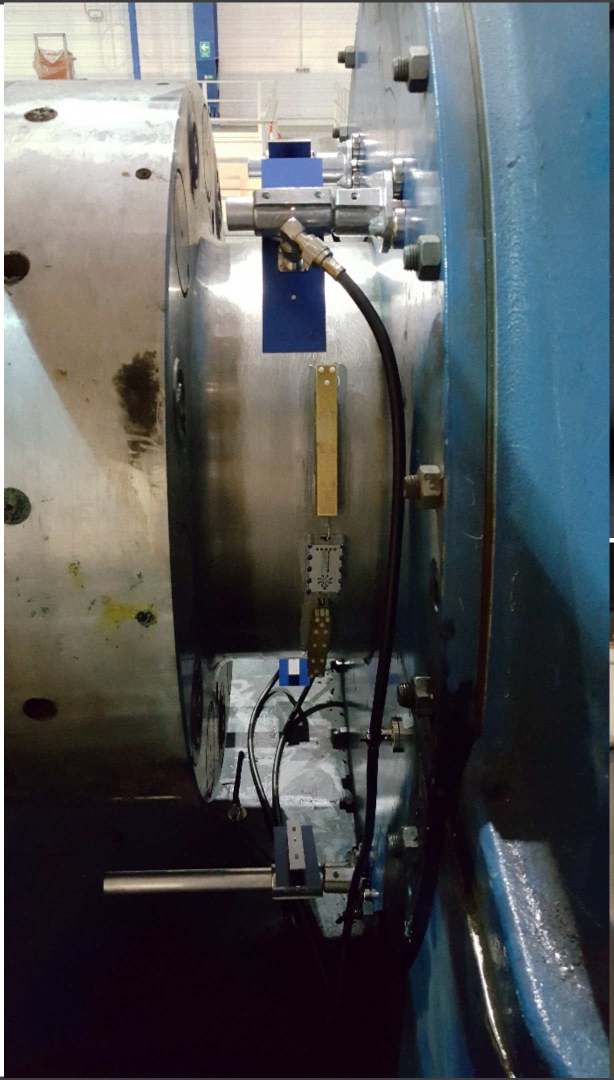


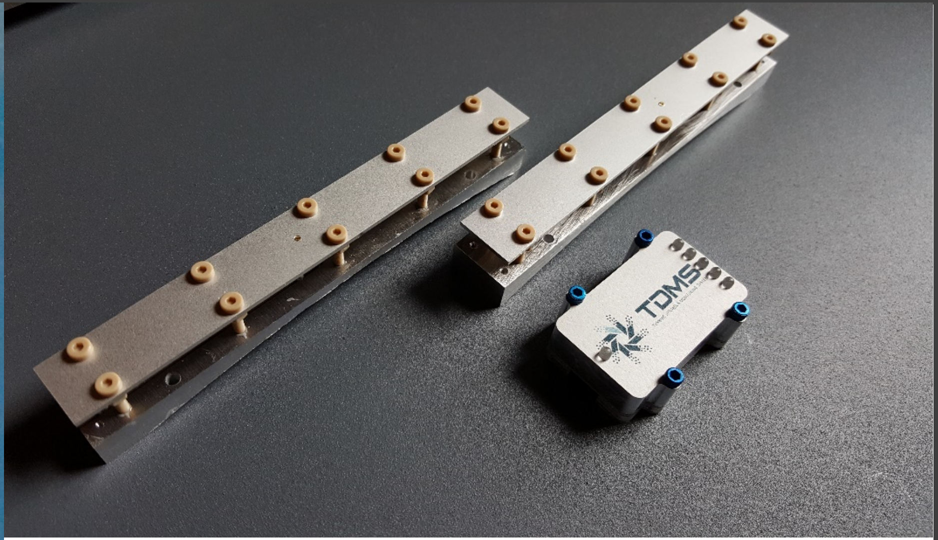
- **Quad telemetry**
  - Torsional strain
  - Tangential acceleration.
  - Lateral strain.
  - Radial acceleration.

- **Battery free wireless**
  - Extended data acquisition.
  - No battery replacement or risks of electrolyte contamination.
  - No inductive ring or high tolerance alignment.

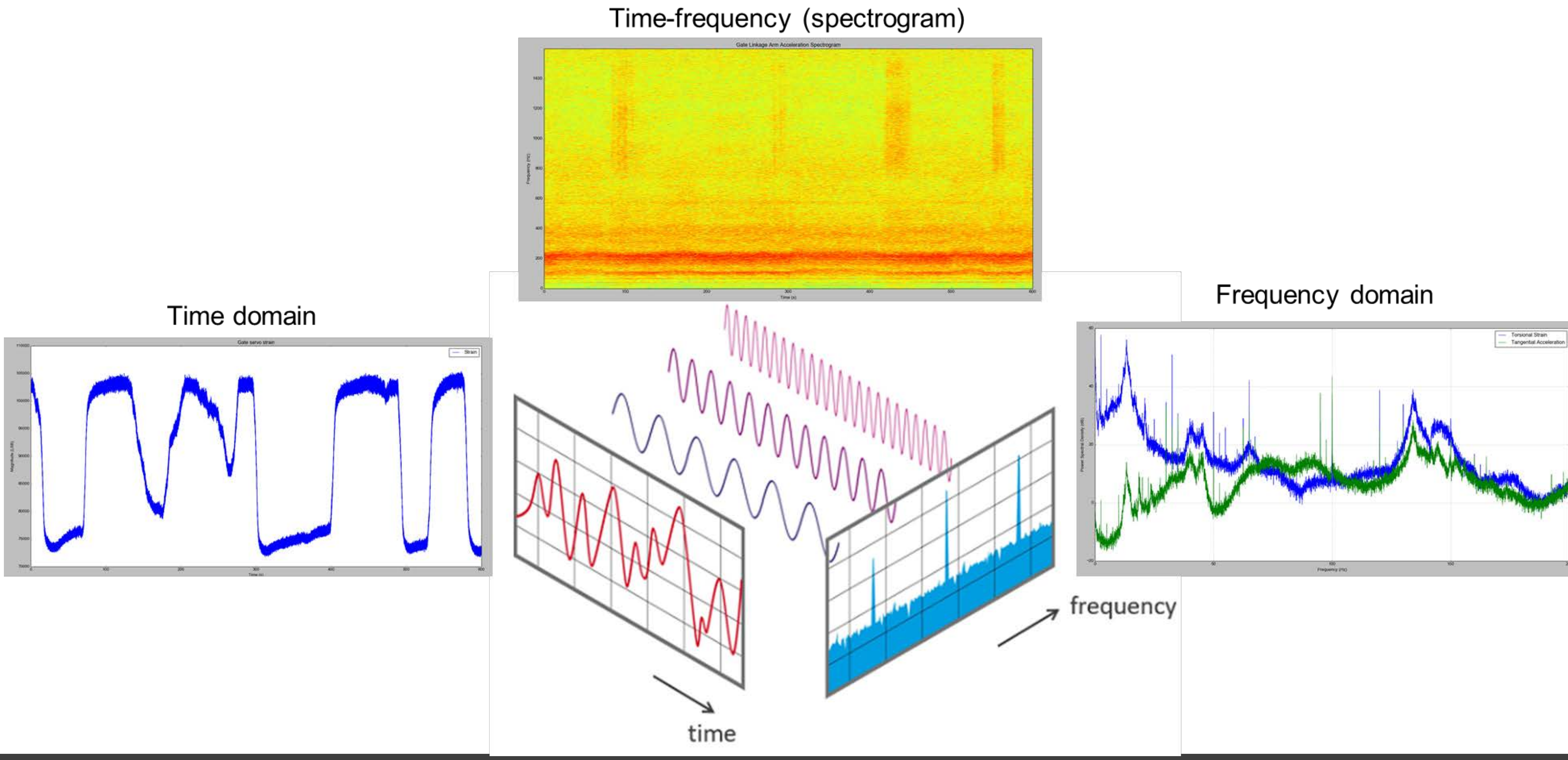
TDMS Commercial System Components

- Quad Telemetry
  - Telemetry module.
  - Antennas.
- Stationary Telemetry
- Stationary antennas





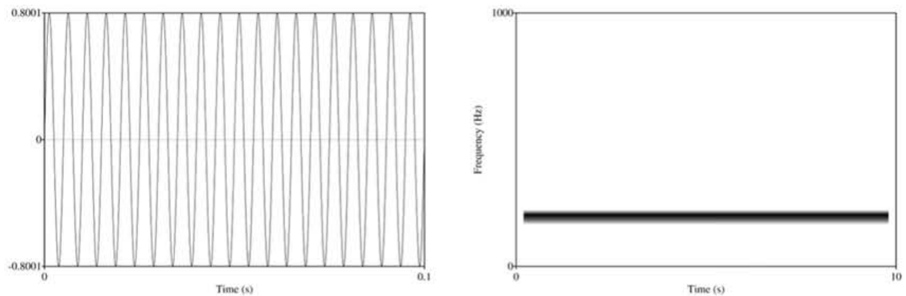
Data analytical facets



Brief introduction to Spectrograms

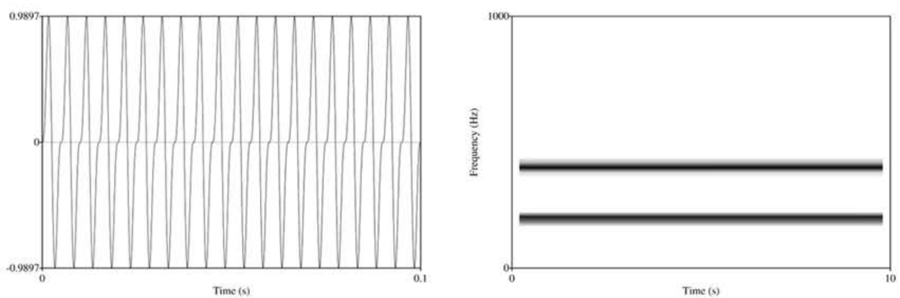
Distinction Between Waveforms and Spectrograms

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

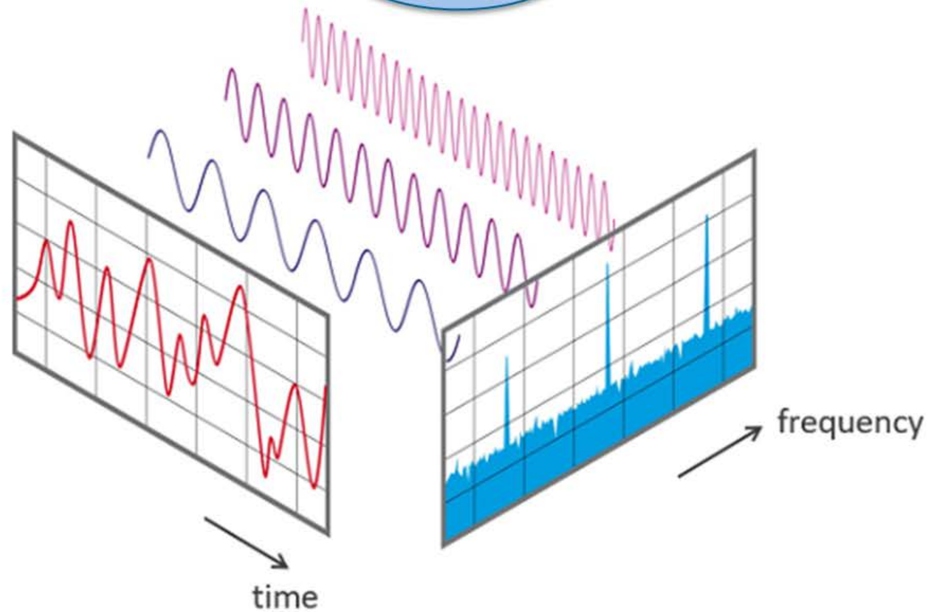


Complex Wave with 200Hz and 400Hz Components

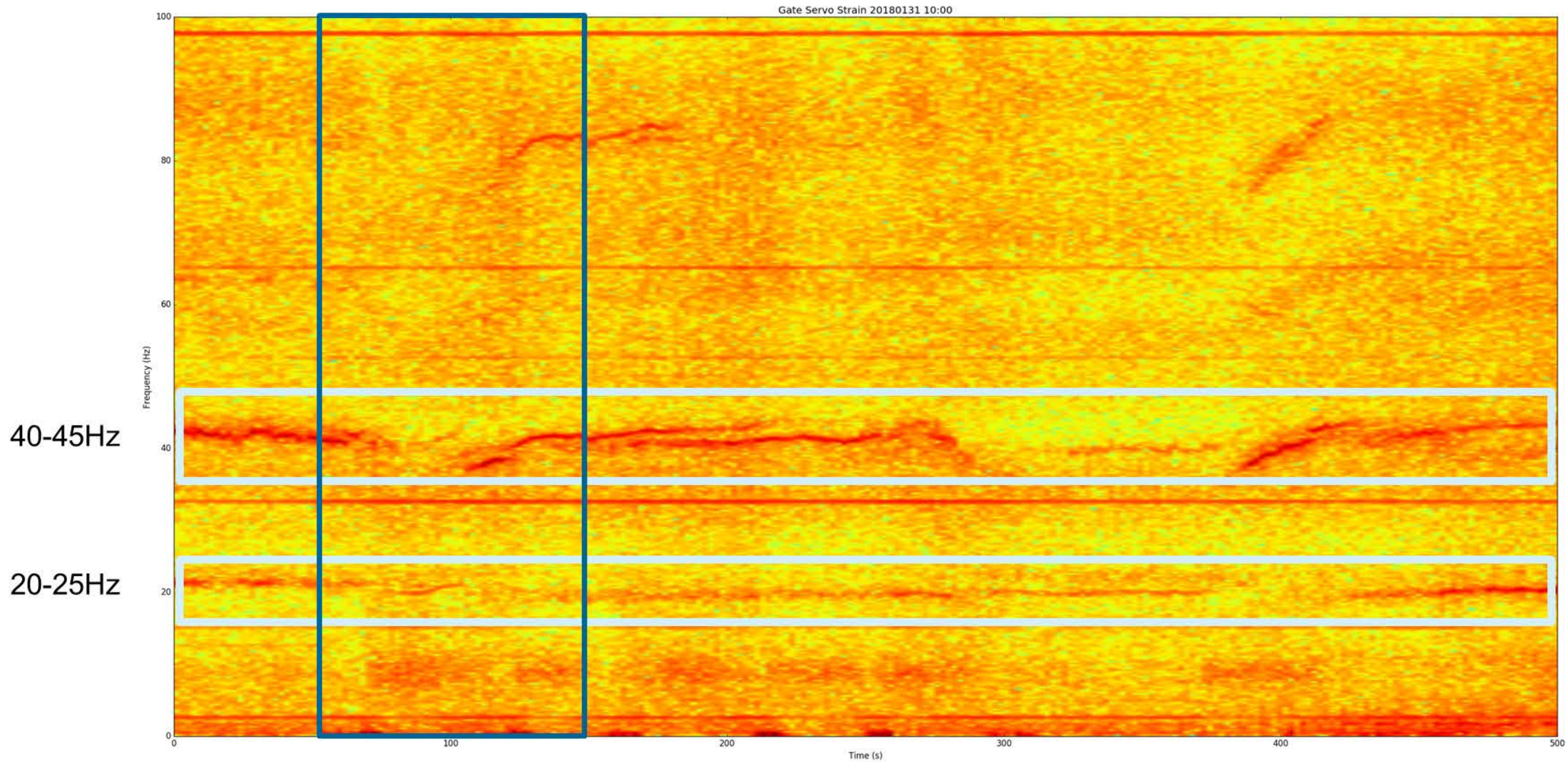
Components have same amplitude



Torsional deflection is not just a static parameter at different MW values. Operational deflection happens across a wide bandwidth of frequency following the mode shapes.



Proof of concept – foundation cracks in hydro applications



Evidence for success in steam turbines

- Similar analogous measurements for hydro turbine-generators
- High signal to noise ratio.
- Frequency accuracy.

- **Practical application of the modeled frequency bands into automated frequency tracking software.**

Automated frequency tracking and vibration analysis

Approach to monitoring

1. Use model to estimate delta-frequencies (changes) associated with severity of cracking.

2. TDMS measures frequencies in-situ.

3. Monitoring analyzers are set up with frequency limits corresponding to the maximum expected delta frequency.

4. **Trend mode frequencies according to regular operating states of the turbine-generator**

Then what?

- EPRI P193 project is currently integrating automated monitoring using TDMS into APR and SCADA systems.
- **Plant data opens the door to associating frequency trends with specific operating states of the TG**
- Example baseline of expected mode frequencies:

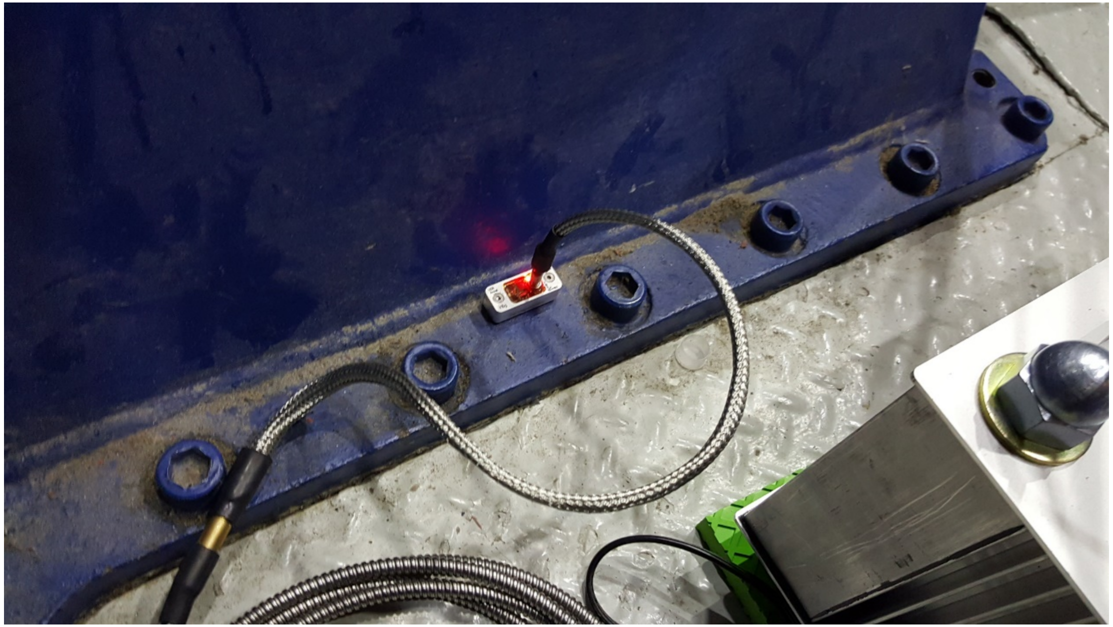
100MW	200MW	300MW	400MW
10.1Hz	10.05Hz	10Hz	9.95Hz
13.8Hz	13.76Hz	13.7Hz	13.68Hz
20.35Hz	20.35Hz	20.33Hz	20.31Hz
40.25Hz	40.2Hz	40.12Hz	…
….			

- **Important to trend frequencies at similar heat and flow states.**

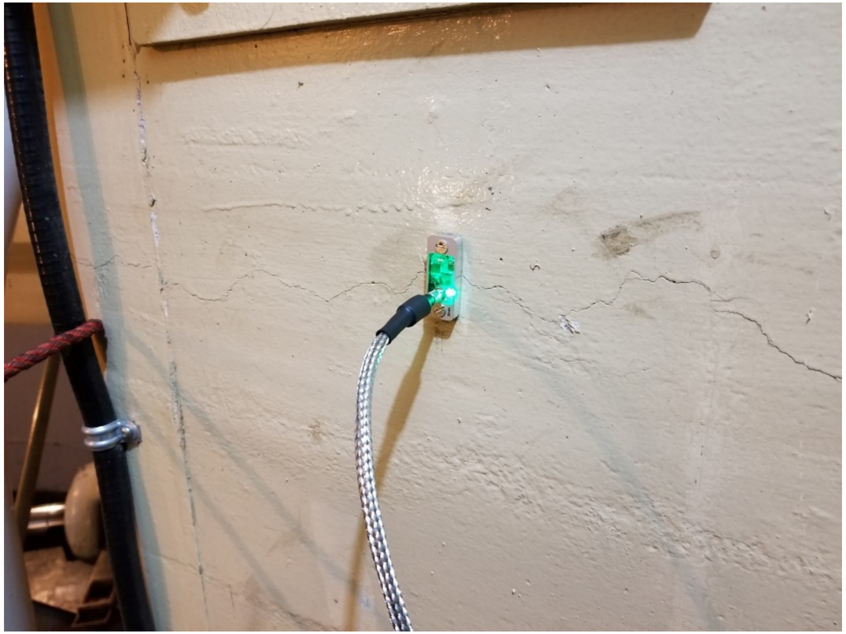
Related sensors increases confidence

- Time synchronous correlation of related sensors is valuable to corroborate the TDMS data and further evidence for crack growth.

Bearing accelerometers

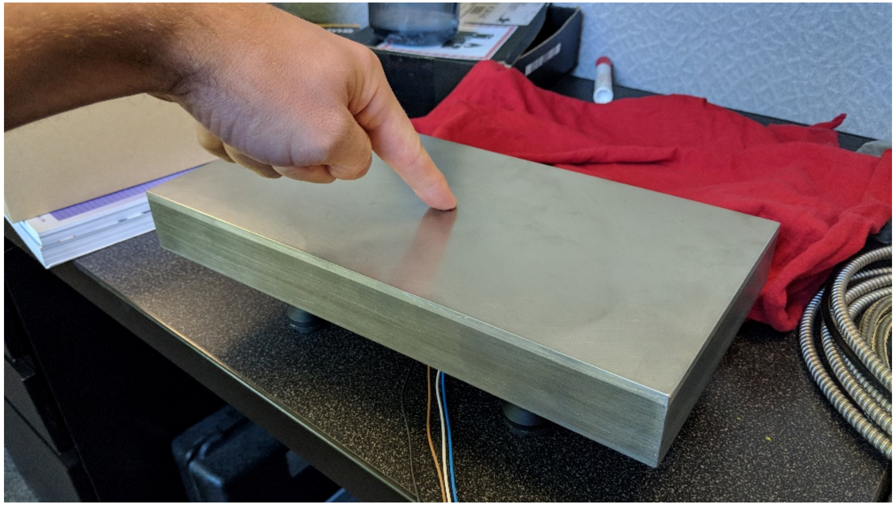


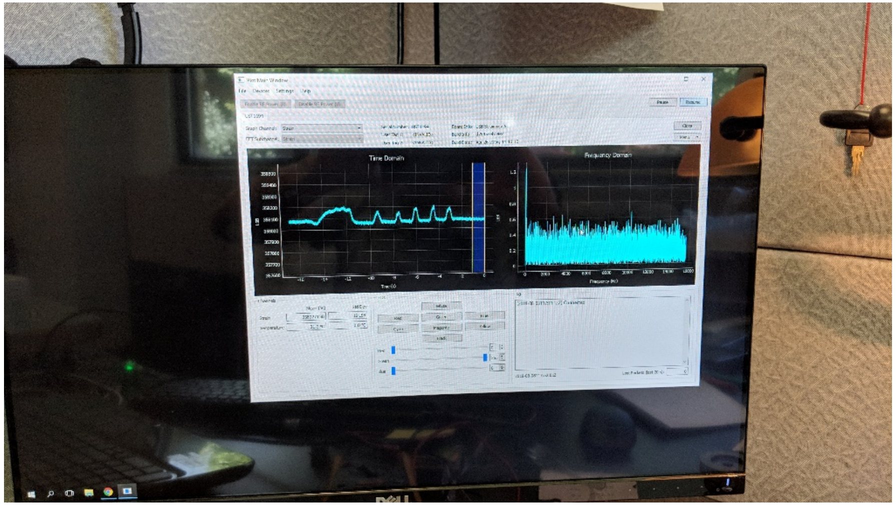
Foundation strain



New sensor classes may also aid in validation

- Suprock is working with Pioneer Motor Bearing to implement high temperature strain sensors cast directly into the babbitt.
  - Capable of withstanding >1200F and the babbitt casting process.
- Early detection of changes in bearing static loading and elastohydrodynamic behavior of the oil film.
- Technology program testing through EPRI under Stan Rosinski.





Conclusion

- The concept of detecting a shaft crack via torsional natural frequency measurements is feasible and has been proven in small scale research and development efforts by others
- More precise/definitive than using lateral vibration measurements
- Some development work still required to apply the approach to field use on large steam turbine generators
- Costs of implementation are significant, but site/fleet-specific issues may justify the investment
- TDMS is the primary sensor for on-rotor monitoring and results can be corroborated to increase confidence by using external sensor classes.

Questions?

Christopher Suprock
Suprock Technologies
casuprock@suprocktech.com
603-686-9954
www.suprocktech.com

Kevin Myers
MPR Associates, Inc.
kmyers@mpr.com
703-519-0416
www.mpr.com