NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Investigation of Various Wind Turbine Drivetrain Condition Monitoring Techniques

Shawn Sheng
Senior Engineer, NREL/NWTC

2011 Wind Turbine Reliability Workshop
August 2-3, 2011
Albuquerque, NM

NREL/PR-5000-52352

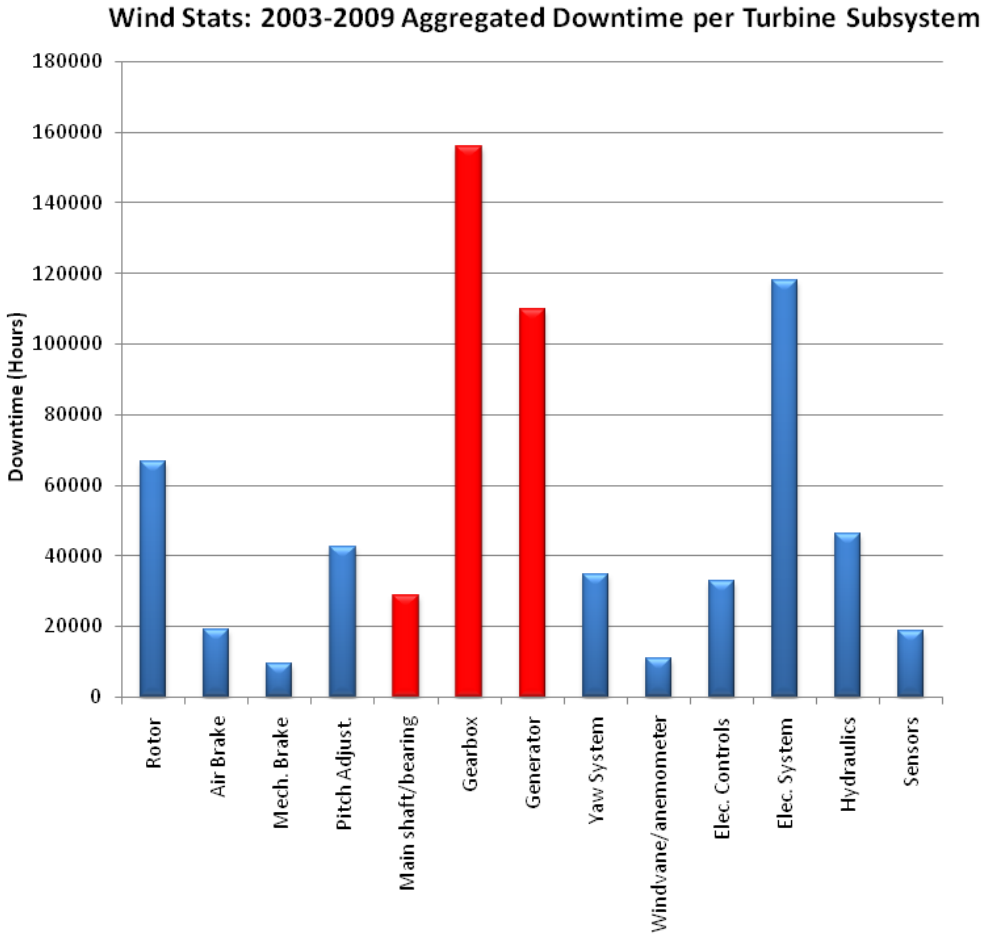
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Outline

- Introduction
  - Downtime caused by turbine subsystems
  - Annual failure frequency of turbine subsystems
  - Cost benefits of condition monitoring (CM)
- Drivetrain CM
  - Approach and rationale
  - Implementation
- Tests
- Results and Observations

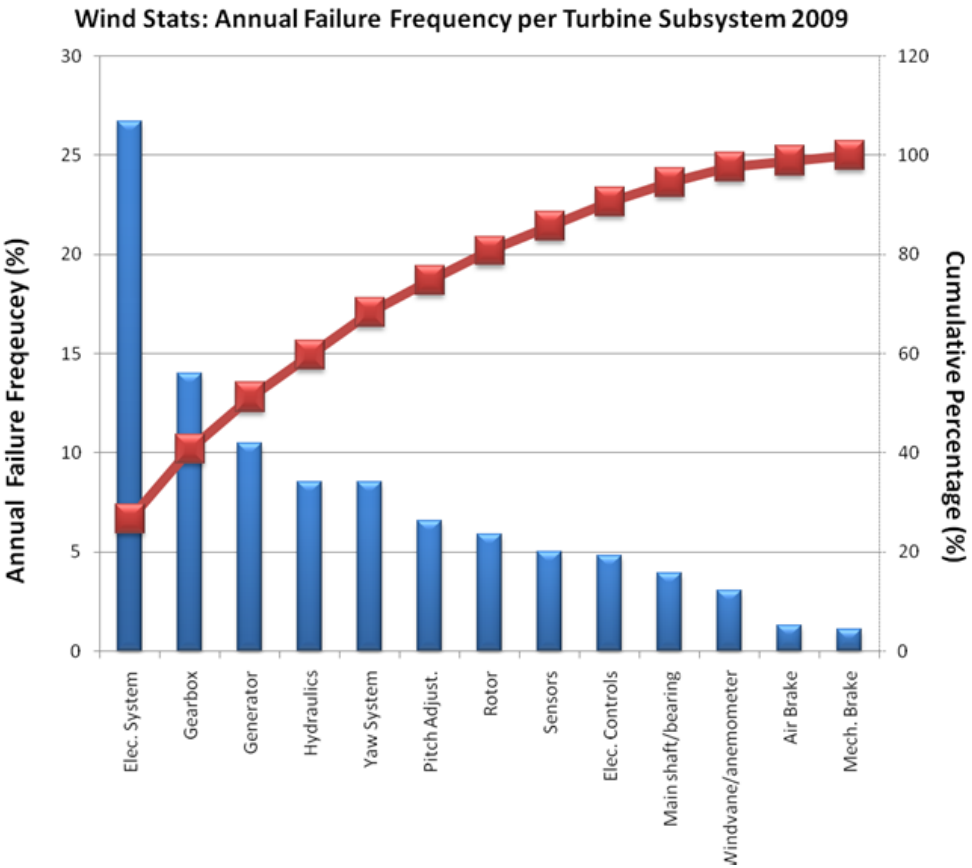
Introduction: Downtime

- Data Source: Wind Stats Newsletter, Vol. 16 Issue 1 to Vol. 22 Issue 4, covering 2003 to 2009[1]
- Based on the data reported to Wind Stats for the first quarter of 2010, the data represents: about 27,000 turbines, ranging from 500 kW to 5 MW.
- Highest: Gearbox
- Top Three: Gearbox, Generator and Electric Systems
- Take crane cost into consideration:
  - Main bearing also needs attention.
  - Electric systems often do not need an expensive crane rental.



Introduction: Annual Failure Frequency

- Data Source: Wind Stats 2009 data
- Top Three: electric systems, gearbox and generator
- 27% equivalent to 0.6 failures/turbine subsystem/year based on data reported by Reliawind*
- Take crane cost into consideration:
  - Reliability improvement first needed on gearbox, generator, main bearing and rotor
  - Health monitoring helps in providing individual turbine health information and extending turbine uptime
  - Condition Monitoring (CM) for first three
  - Structural health monitoring for rotor



*source: www.reliawind.eu/files/publications/pdf_13.pdf

Introduction: Cost Benefits

- Experience at Schenck [2]

Operator / Owner	# of Turbines Duration of Service	Costs CMS plus Service in €	Detected Damages	Costs unplanned Replacement Costs planned Repair in €	Total Savings in €
enviaM	15 WTG's 5 years	150,000	3 x Gearbox	405,000 101,250	303,750 In 5 years
e.disnatur	130 WTG's 5 years	1,300,000	12 x Gearbox 40 x Generator bearing	4,620,000 1,155,000	3,465,000 In 5 years
juwi Management	59 WTG's 3 years	472,000	20 x Gearbox 1 x Generator bearing 1 x Main bearing	2,811,000 702,750	2,108,250 In 3 years

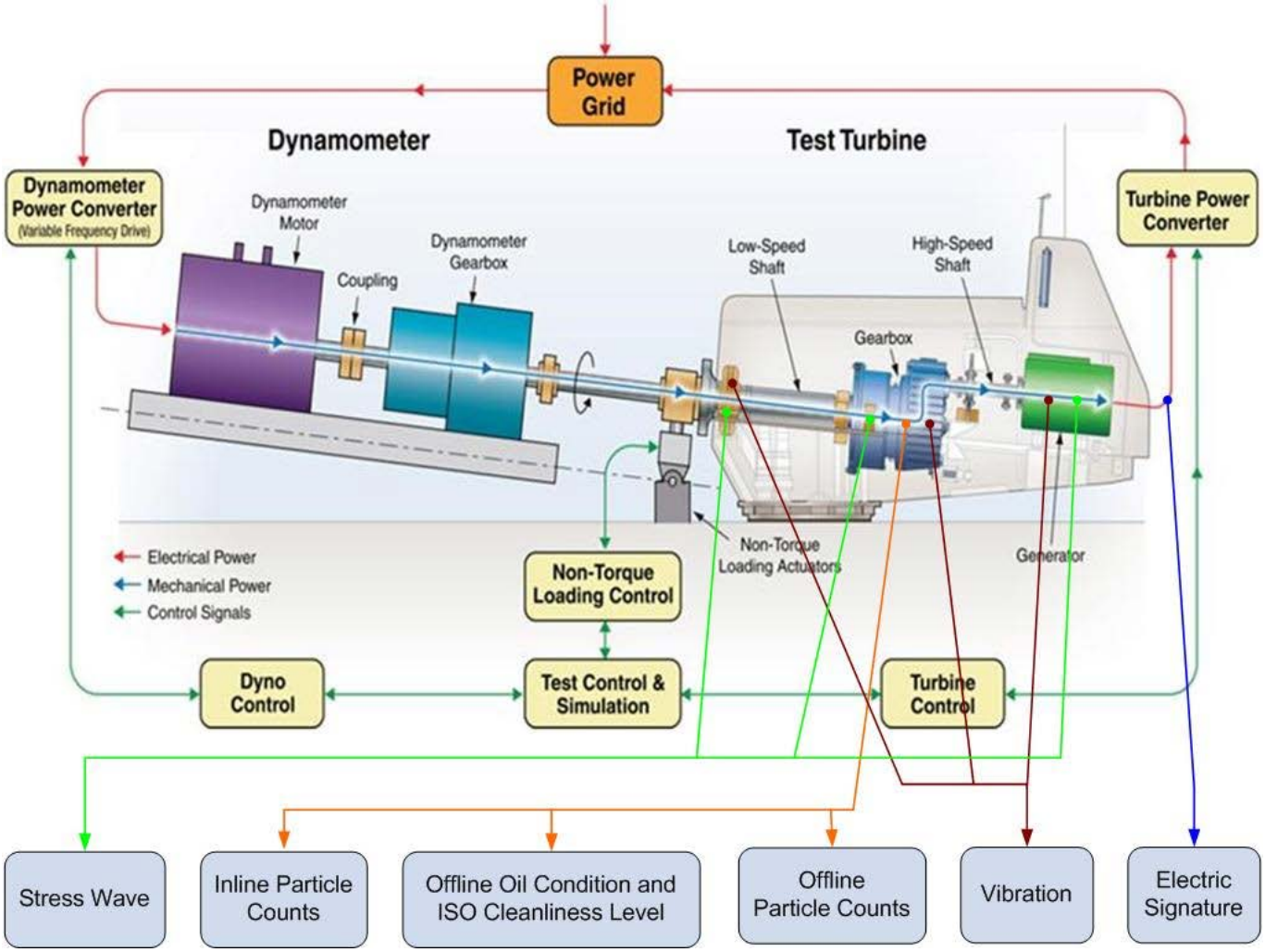
- Based on 1.5 MW wind turbine with replacement costs of about €150,000 for gearbox, €38,000 for a generator and €25,000 for a main bearing (DEWI)
- Costs for planned repair < 30% for unplanned replacement (DEWI)
- Cost per CM system approximately €5,000 plus €1,000 per year per wind turbine (service)
- Above cost savings do not include loss of production

Return on Investment for all three cases less than 3 years

Drivetrain CM: Approach and Rationale

- One area of research under Gearbox Reliability Collaborative (GRC)
- Integrated Approach
  - Acoustic emission (specifically, stress wave)
  - Vibration analysis
  - Oil debris and condition monitoring techniques
  - Electric signature-based technique
- Rationale
  - Each technique has its own strengths and limitations
  - Combine active machine wear detection capability of lubrication oil monitoring techniques with crack location pinpointing capability of AE and vibration analysis
  - Investigate potential technique for direct-drive turbines

Drivetrain CM: Implementation

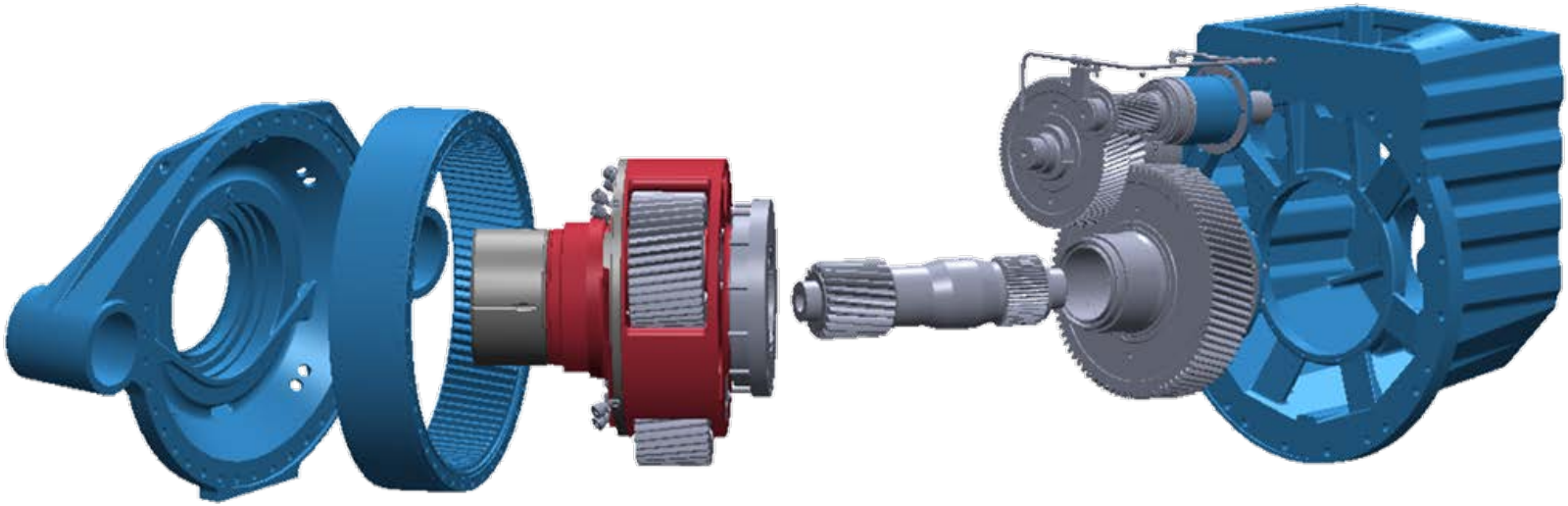


- Stress wave analysis
- Vibration analysis
- Inline (main filter loop) particle counting
- Offline filter loop particle counting, oil condition monitoring (i.e., moisture, total ferrous debris, and oil quality)
- Electric signature monitoring
- Periodic oil sample analysis

As a research project, this set up is beyond the typical drivetrain CM configuration seen in the industry.

Tests: Test Articles

- Two gearboxes rated at 750 kW
  - One planet stage and two parallel stages
  - Redesign
    - Floating sun, cylindrical roller planet bearings, tapered roller bearings in parallel stages, pressurized lubrication, offline filtration and desiccant breather
  - Up to 150 channels of measurements for loads, displacements, and temperature



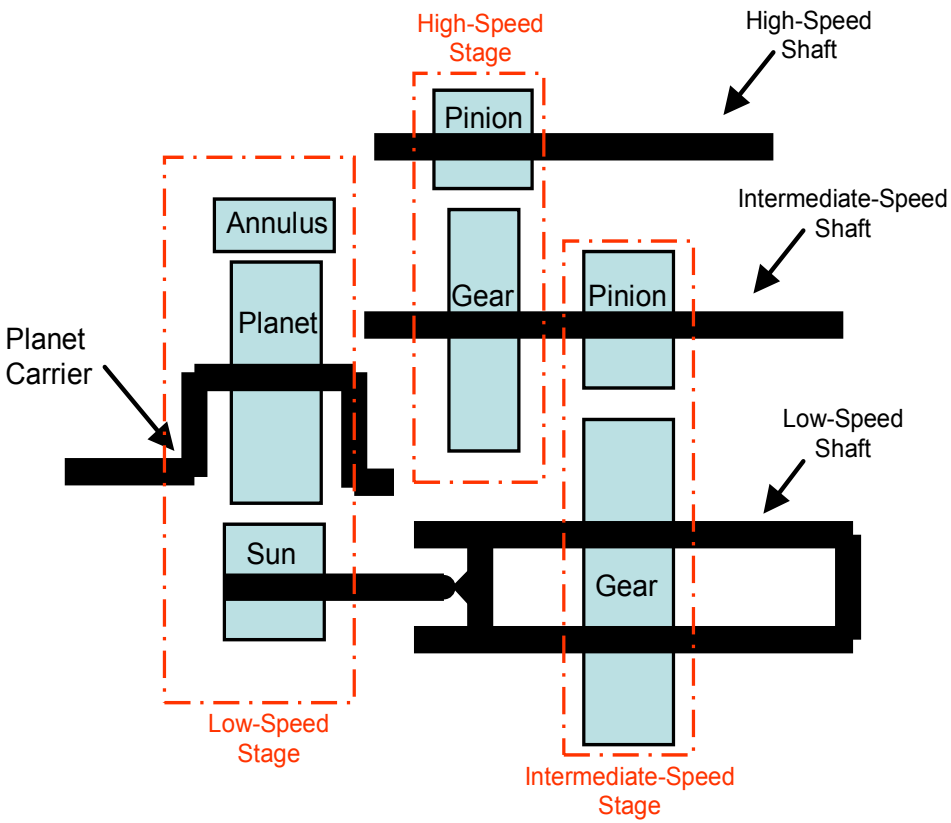
Tests: Conducted Tests

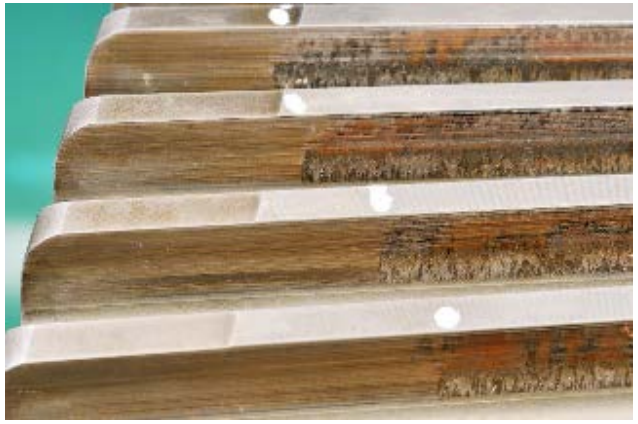
- Dynamometer test of GRC gearbox #1: run-in
- Field test of GRC gearbox #1
- Dynamometer test of GRC gearbox #2: run-in and non-torque loading
- Retest of GRC gearbox #1 in the dynamometer

NREL 2.5 MW Dynamometer/PIX16913

Tests: Damaged Gearbox

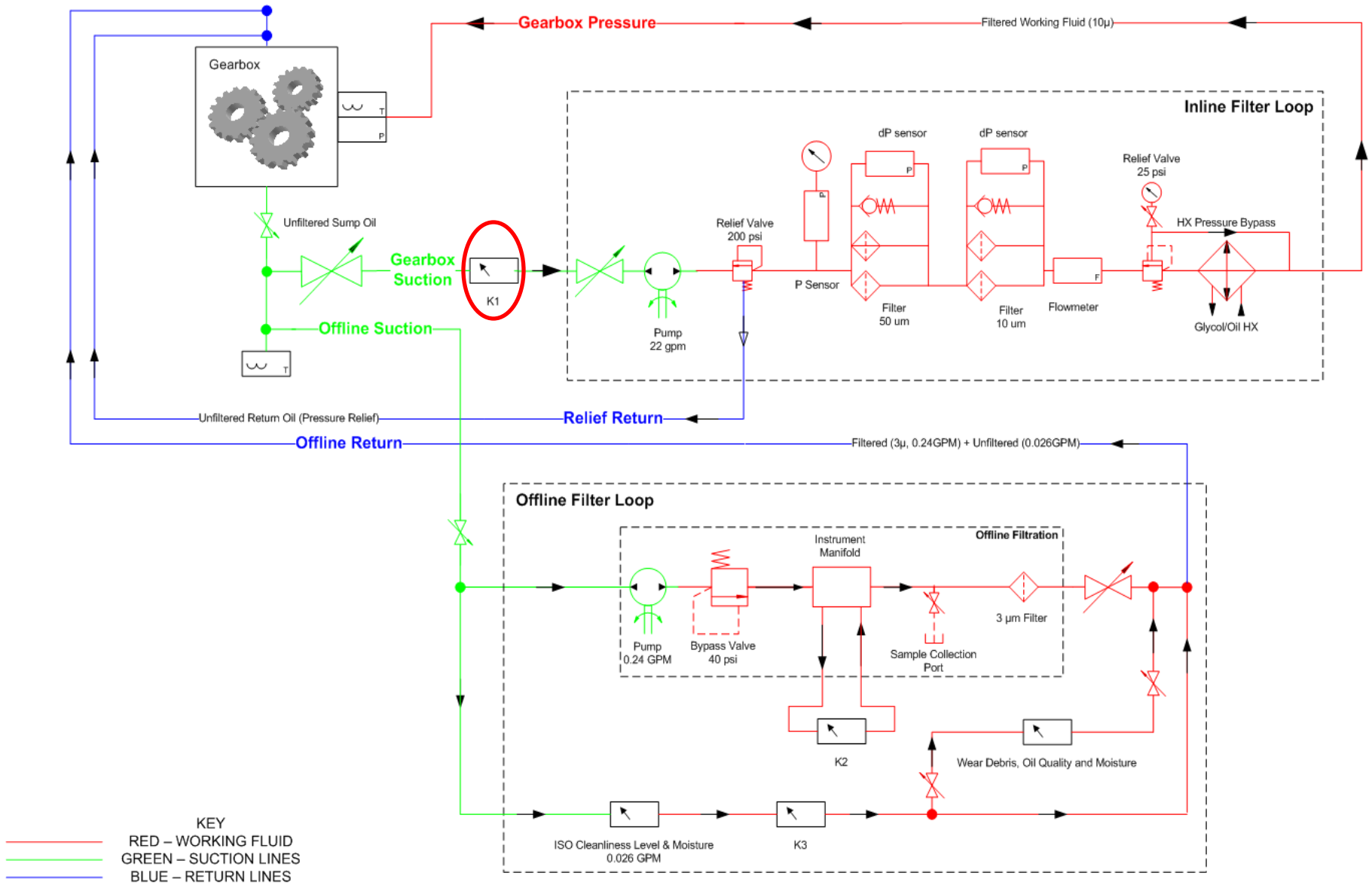
1. Completed dynamometer run-in test
2. Sent for field test: experienced two oil losses
3. Stopped field test
4. Retested in the dynamometer under controlled conditions



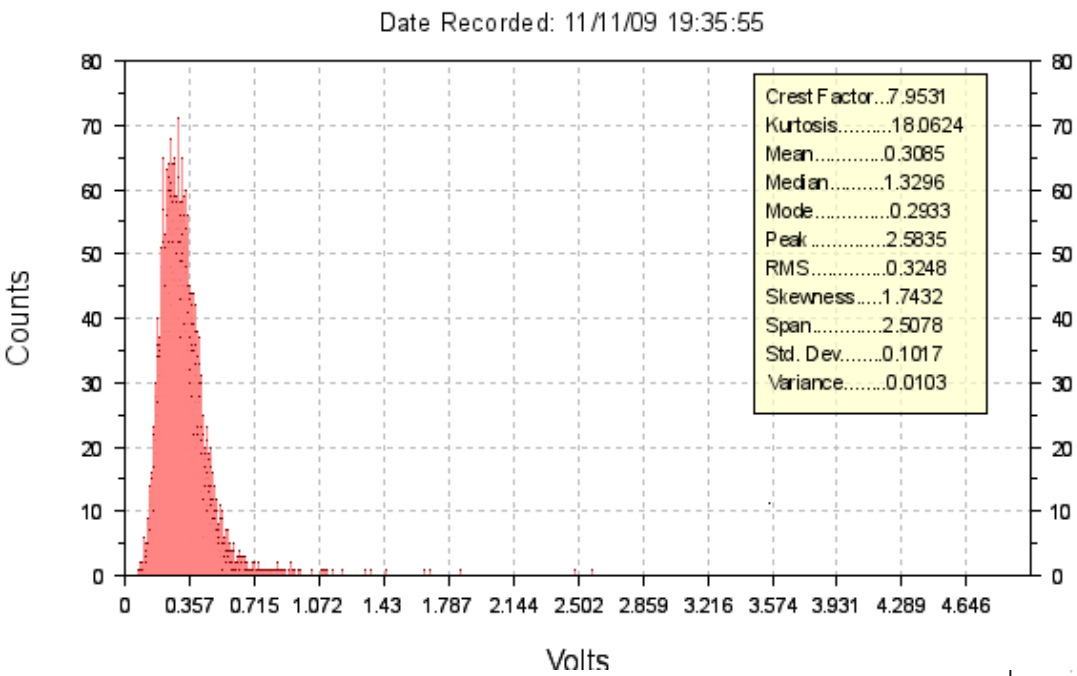


High-Speed Stage Gear

Tests: Lubrication System Diagram

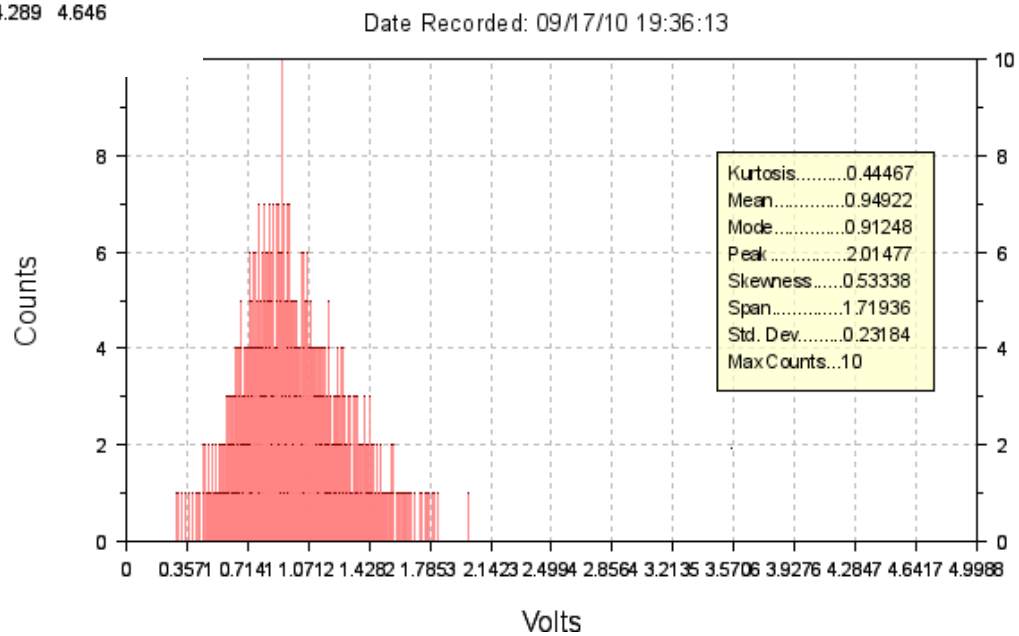


Results: Stress Wave Amplitude Histogram

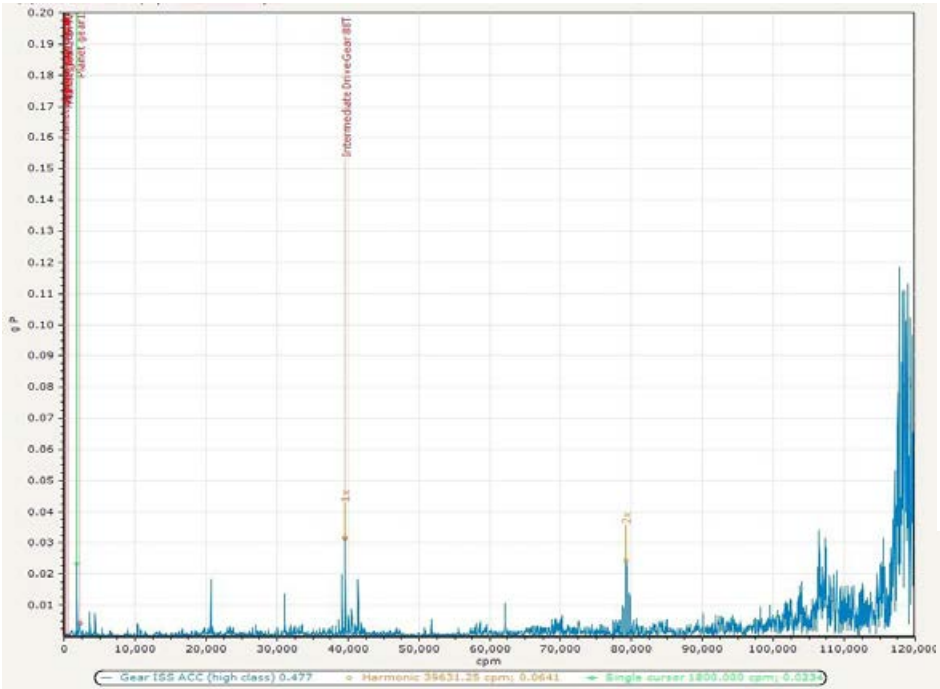


- Parallel stages sensor
- GRC gearbox #2 dynamometer test (left) indicated healthy gearbox behavior

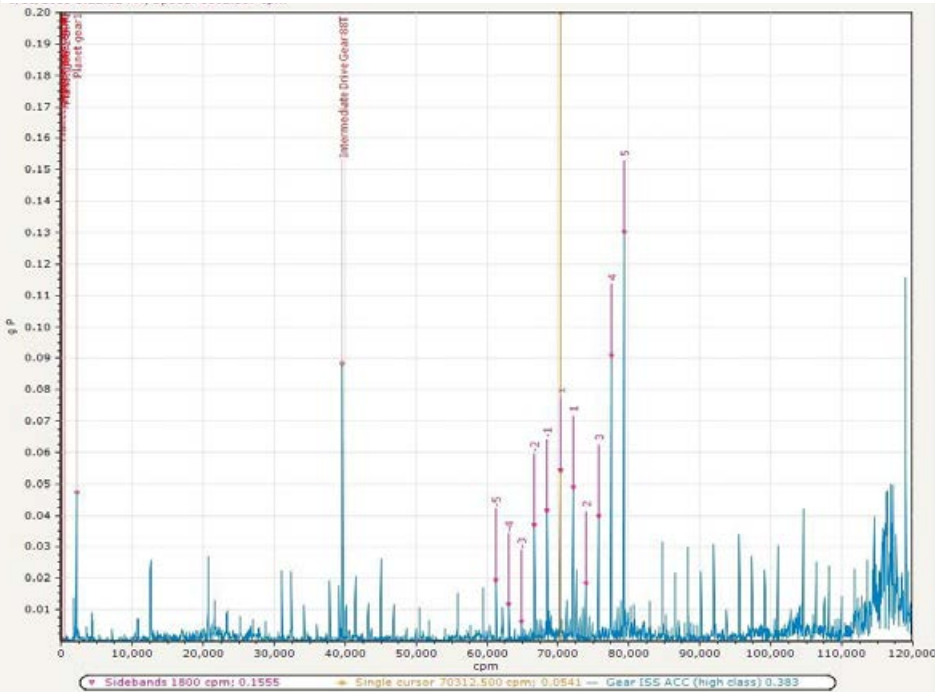
- Dynamometer retest of GRC gearbox #1 (right) indicated abnormal gearbox behavior



Results: Vibration Analysis

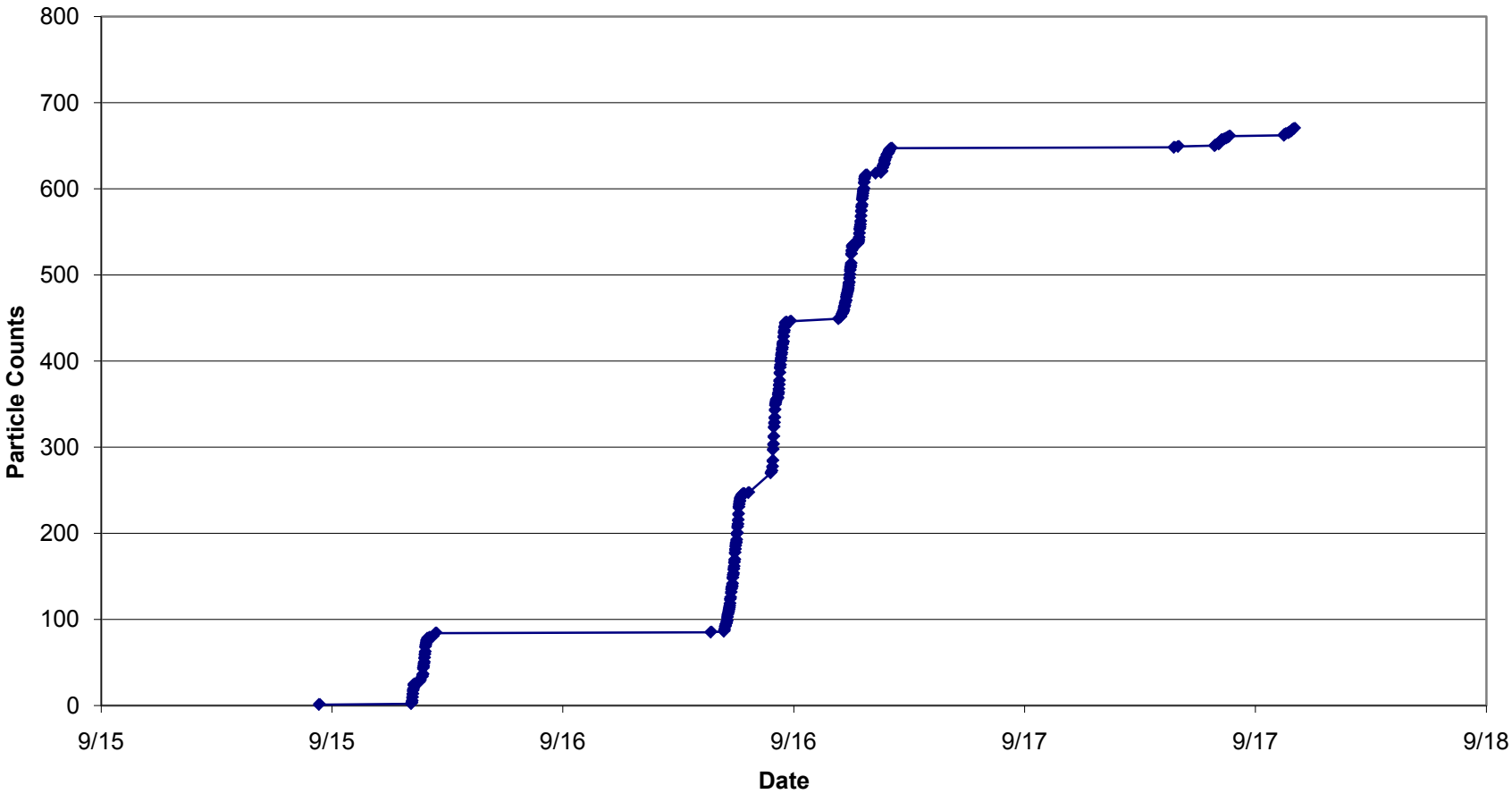


- Intermediate speed shaft sensor
- GRC gearbox #2 dynamometer test (left) indicated healthy gearbox behavior



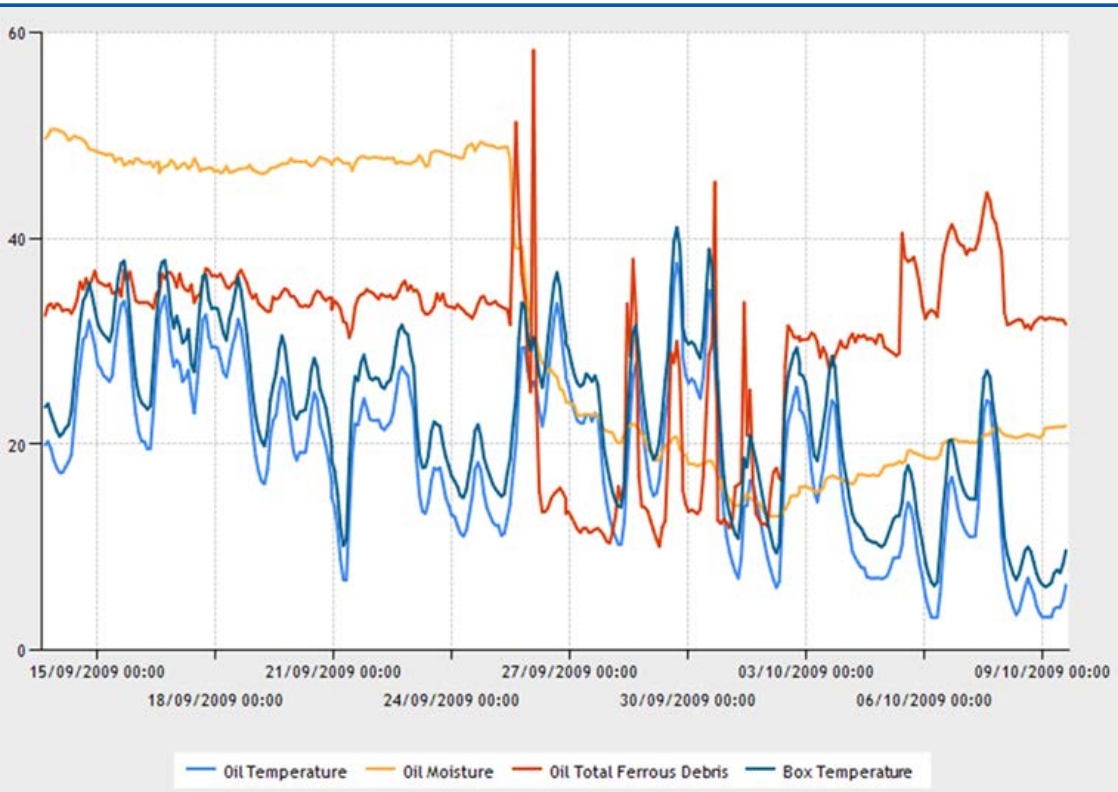
- Dynamometer retest of GRC gearbox #1 (right) indicated abnormal gearbox behavior
  - More sideband frequencies
  - Elevated gear meshing frequency amplitudes

Results: Oil Debris Monitoring

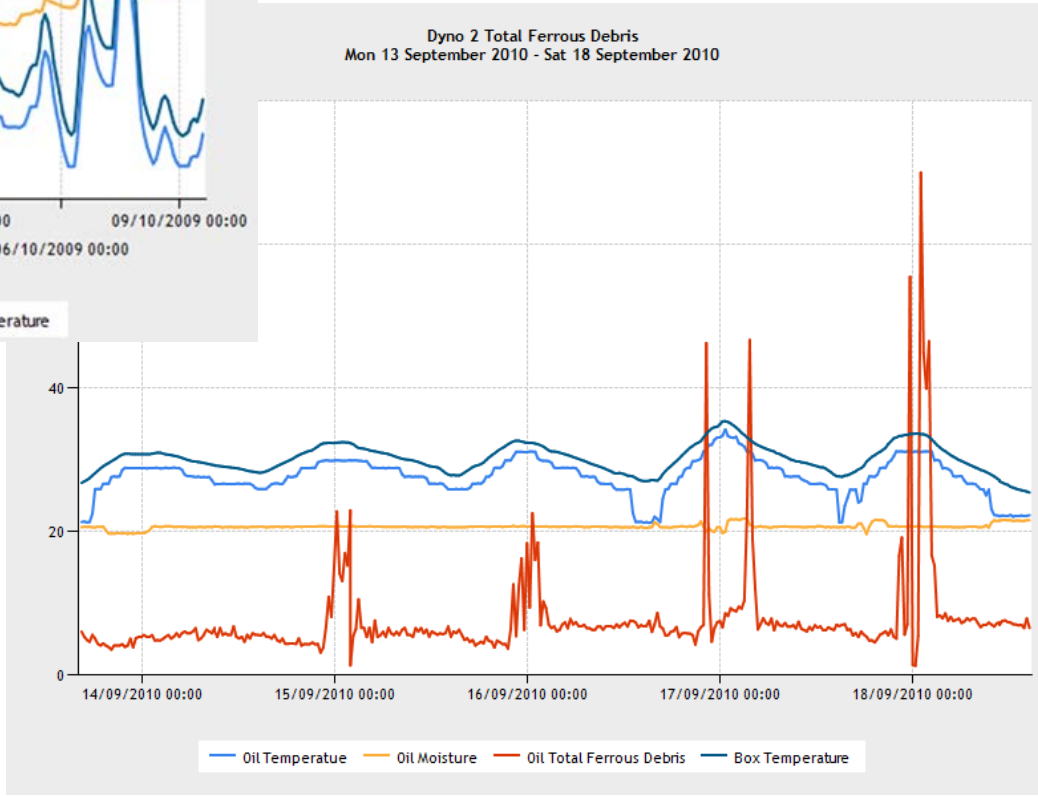


- Particle generation rates:
  - Damaged GRC gearbox #1: 70 particles/hour on 9/16
  - Healthy GRC gearbox #2: 11 particles over a period of 4 hours

Results: Oil Condition Monitoring



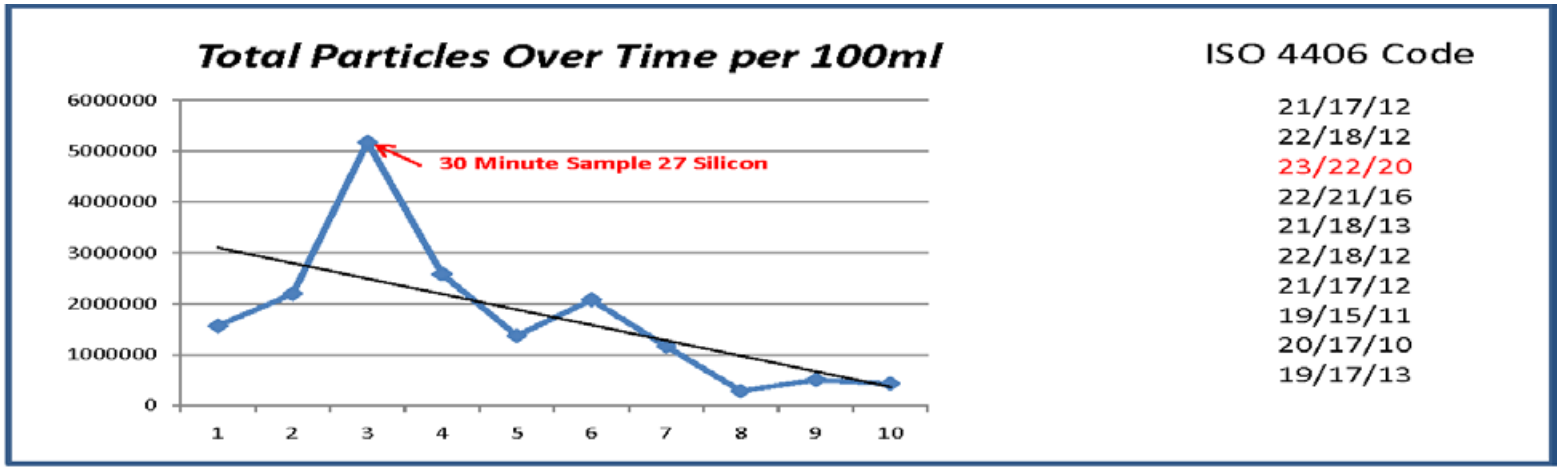
- Field test of GRC gearbox #1 (left):
  - Wild dynamics
  - Possible damage



- Retest of GRC gearbox #1 (right):
  - Well controlled test conditions
  - Possible damage

Results: Oil Sample Analysis

- Results: GRC gearbox #2
  - Particle counts: important to identify particle types[3]



  - Element identification

Metals								
Iron ppm		2	<1	1	1	1	1	1
Aluminum ppm		4	<1	<1	<1	<1	<1	<1
Chromium ppm		4	<1	<1	<1	<1	<1	<1
Copper ppm		2	<1	1	1	1	1	1
Lead ppm		1	<1	1	1	1	1	1
Tin ppm		4	<1	<1	<1	<1	<1	<1
Nickel ppm		4	<1	<1	<1	<1	<1	<1
Silver ppm		4.5	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Silicon ppm		20	<1	3	4	3	3	5
Sodium ppm			<2	<2	<2	<2	<2	<2
Boron ppm			<1	2	2	1	1	1
Zinc ppm			1	21	24	24	24	29
Phosphorus ppm			4	31	38	31	31	54
Calcium ppm			11	24	27	23	24	24
Magnesium ppm			<1	<1	<1	1	<1	<1
Barium ppm			3	8	9	6	7	7
Molybdenum ppm			<1	11	12	11	11	12
Potassium ppm			<3	<3	<3	<3	<3	<3

Reference Limits

Analysis Results

Observations

- Stress wave amplitude histogram appears effective for detecting gearbox abnormal health conditions.
- Spectrum analysis of vibration signal (or stress waves) can, to a certain extent, pinpoint the location of damaged gearbox components.
- Oil debris monitoring, specifically particle counts, is effective for monitoring gearbox component damage, but is not effective for damage location.
- Damaged gearbox releases particles at increased rates.

Observations (*Cont.*)

- Oil condition monitoring, specifically moisture, total ferrous debris and oil quality:
  - More data is required to understand oil moisture and quality.
  - Oil total ferrous debris appears indicative for gearbox component damage.
- When obtaining particle counts through oil sample analysis, attention should be given to identifying particle types.
- Periodic oil sample analysis may help pinpoint failed component and root cause analysis.
- Electric signature-based technique did not reveal any gearbox damage in this study.

References

1. Sheng, S. and Veers, P. "Wind Turbine Drivetrain Condition Monitoring – An Overview," *Machinery Failure Prevention Technology (MFPT) Society 2011 Conference Proceedings*, Virginia Beach, VA, USA, May 10-12, 2011.
2. Kewitsch, R. "Optimizing Life Cycle Costs (LCC) for Wind Turbines by Implementing Remote Condition Monitoring Service," presented at *the AWEA Project Performance and Reliability Workshop*, January 12–13, 2011, San Diego, CA.
3. Herguth, W. "Gearbox Reliability Collaborative Dynamometer Test Results," presented at *the NREL GRC All Member Meeting*, Feb. 2-3, 2010, Golden, CO.
4. Sheng, S. "Investigation of Various Condition Monitoring Techniques Based on a Damaged Wind Turbine Gearbox," to be presented at *the 8th International Workshop on Structural Health Monitoring 2011*, Stanford, CA, USA, September 13-15, 2011.

Thanks for Your Attention!

Special thanks go to GRC CM partners: CC Jensen, Castrol, Eaton, GasTOPS, Kittiwake, Herguth Laboratories, Lubrizol, Macom, SKF, SKF Baker Instruments, and SwanTech!

NREL's contributions to this presentation were funded by the Wind and Water Power Program, Office of Energy Efficiency and Renewable Energy of the U.S. Department of Energy under contract No. DE-AC02-05CH11231. The authors are solely responsible for any omissions or errors contained herein.