Statistics on condition monitoring of 283 turbines for 3800 turbine months

An internal study of monitoring performance, this paper charts the effectiveness of condition monitoring versus key metrics. The data set encompasses 283 wind turbines from several wind farms, under daily monitoring contracts, chosen to cover a range of climates and ages. During the period 20 main component failures were detected, confirmed by inspection and either repaired/replaced or now planned for replacement or life extending maintenance/operation. Figure 1 provides a breakdown.

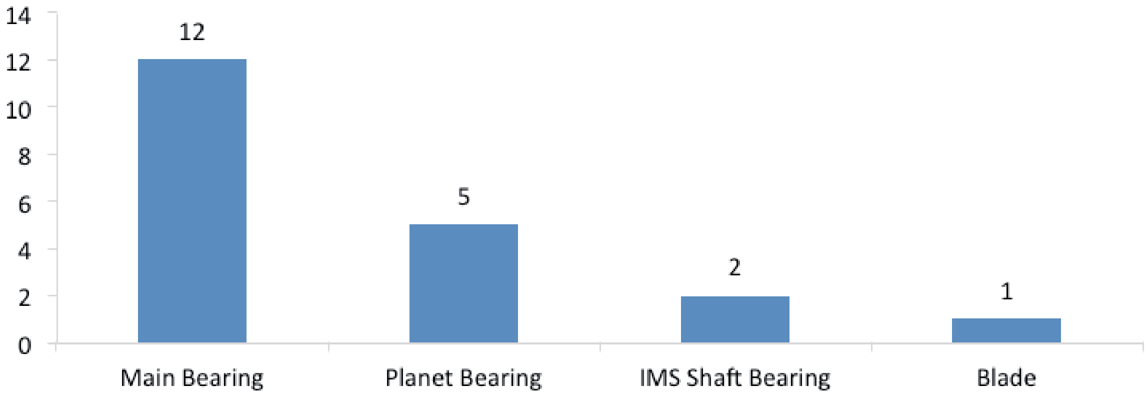

Figure 1 – Count of detected failures (confirmed) by component

Monitoring Architecture

To perform effective vibration condition monitoring, all that is required of the hardware is appropriate and reliable data acquisition, it needs to provide a feed from the accelerometers (generally 4-8 sensors placed close to the bearings) with the appropriate settings for sampling duration and frequency. The data can then be processed in external software to allow for flexibility in signal processing. Typically for the low speed side – main bearing/planet bearing – sample rates can be low, around 200 Hz, and the record lengths long. For the high speed side it's the other way around, short sample times, say 1s, and high sample rates, such as 6.4kHz. A power and speed value typically comes with each acceleration record.

Romax developed a Cloud based software, for in-house and customer use; Fleet Monitor™. It interfaces with condition monitoring hardware (which is principally a data acquisition box), pulls these unprocessed acceleration records (raw time series), and performs advanced signal processing and alarm handling to detect failures and provide ease of use in implementing a continuous improvement approach to detection algorithms and alarm rules. The results and statistics within this paper are derived using Fleet Monitor™ and this approach.

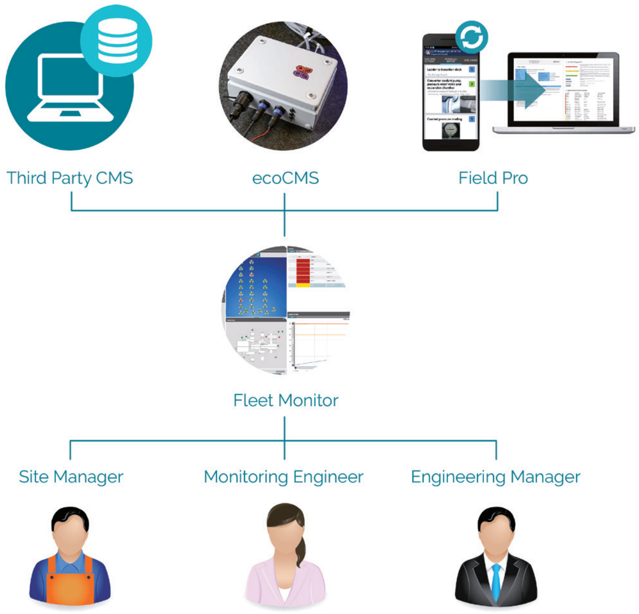

Figure 2 – Overview of Fleet Monitor architecture

Some important definitions

FAULT DETECTION AND DIAGNOSIS

Fault detection and diagnosis may be performed by vibration data signal processing (a lot of complex maths, principally frequency analysis) that is applied to isolate the vibration due to a fault, say a broken tooth or spalled bearing, then distinguish this from vibration that is normal (i.e. vibration from running several MW of power through a gearbox). The detection indicates that a fault is present (alarm), the diagnosis is pinpointing the location. Alarm performance is measured by certain classifications:

The detection and diagnosis are classified by statistical hypothesis testing into Type I or II errors to reflect on alarm performance. Basically, Type I is a false alarm, Type II is a failure that was not detected.

- **True Positive:** Fault detected and confirmed as a failure by inspection or during repair
- **False Positive (Type I error):** Fault detected and confirmed to not be a failure
- **False Negative (Type II error):** Actual failure was not detected first by condition monitoring
- **True Negative:** No alarms, no failures

Careful consideration should be taken as damage may not be present in the inspection area. As well, damage on another component may simulate damage you are looking for and trigger an alarm.

STATISTICS ON DETECTION

After classifying successes and errors for fault detection, for all the alarms raised to the customers under the monitoring service, the monitoring effectiveness can be evaluated (and the statistics also provide your metrics for continuous improvement). It is also beneficial to compare different methods, or combinations of alarms, detecting the same failure. The best alarm has the highest true positives, lowest false alarms and no false negatives. For the 283 turbines and 3802 turbine operating months, the following charts have been compiled (Figure 3). For the main bearings, 92% of past and current alarms were confirmed as true positives, and 8% were false alarms. For the planet bearings, 89% are confirmed as true positives and 11% were not detected first by the vibration monitoring, but rather by debris accumulation in the filters. The IMS bearing has similar results, but a smaller population. Only one blade alarm occurred and was a true positive, so this pie chart is not shown.

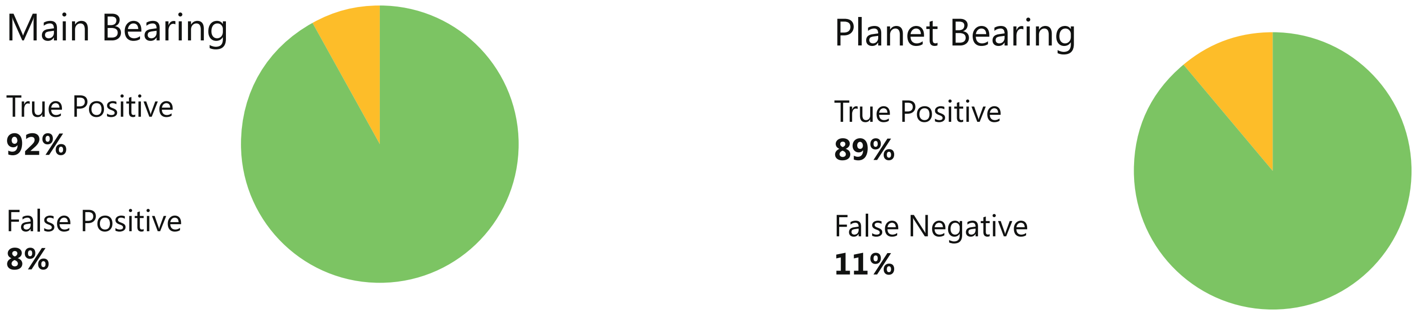

Figure 3 – Detection statistics for alarms on three common failure issues. Note "to be confirmed" represents the current alarms that are in the backlog for inspections. Inspections are typically conducted 1-3 months after first detection.

All of the alarms can be combined (Figure 4) for overall statistics. The metrics on the monitoring team's performance are quite good, 7% false negatives (missed failures) and 4% false positives (false alarms). The 89% that are true positives represent opportunities for savings and making the ROI on condition monitoring.

It should be noted that false alarm rates can be tuned depending on requirements. Setting different alarm levels and thresholds in the monitoring software produces a different false alarm rate. For example, engineers monitoring a nuclear power station or passenger aircraft will happily accept a higher false alarm rate in return for a small increase in true positives. A wind farm operator, however, generally wants to strike a balance based on cost and not call out too many inspections in response to false positives.

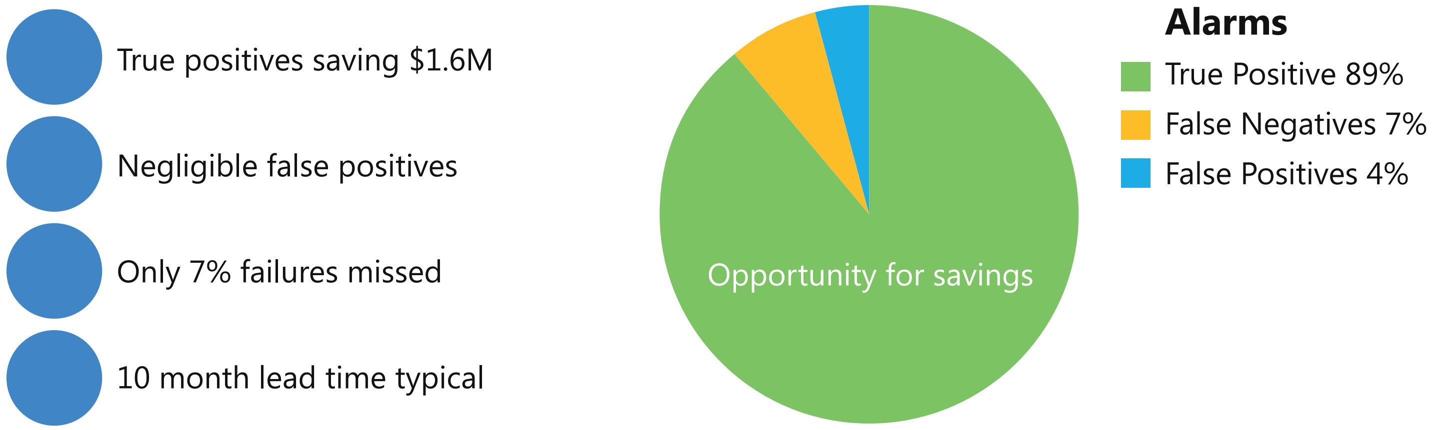

Figure 4 – Detection statistics for all alarms. Note "to be confirmed" represents the current alarms that are in the backlog for inspections. As Romax consistently provide long lead times the sites typically schedule inspections 1-3 months after first detection. As the backlog clears new faults emerge.

LEAD TIMES FOR DETECTION AND VALUE GENERATED

For each of the true positives, the date that the client was notified of an issue was recorded and subtracted from the date of repair, providing a detection lead time (Figure 5). As these issues were principally bearing faults the lead times are very good (gear tooth cracks tend to progress quickly, while bearing faults may take years to progress to complete failure). The results show lead times generally of 10-12 months. There is a wider spread on planet bearings as it's the most challenging damage to detect in a wind turbine gearbox; the very technical reasons: 1. A time varying stiffness in the structural transmission path, making the signal distorted; 2. Modulation from both bearing rotation and planet carrier rotation, making signal demodulation more challenging; 3. Low fault frequencies putting them in a similar frequency ranges to dynamic changes in speed and load, making a steady measurement period more challenging to obtain.

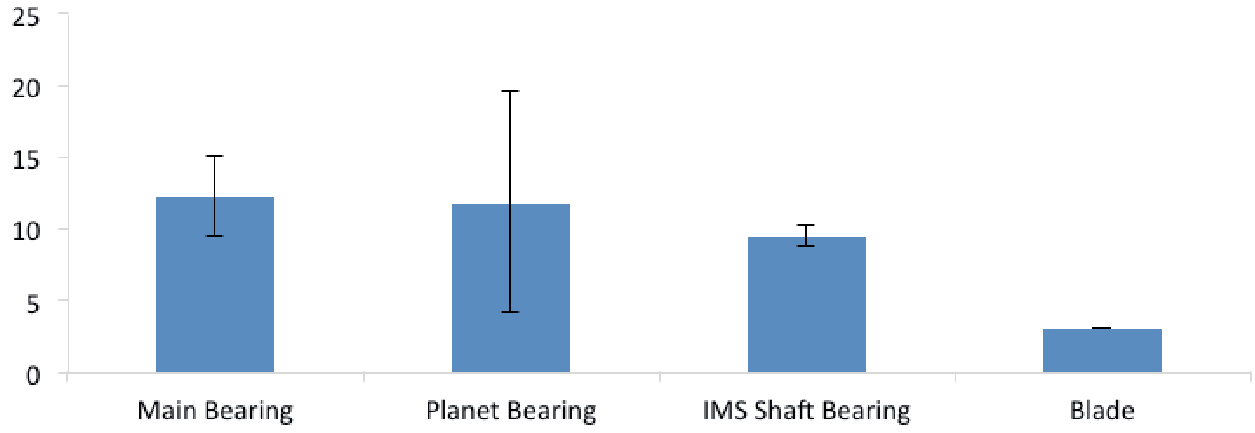

Figure 5 – For true positives, the average detection lead time before repair (months).

LEAD TIMES FOR DETECTION AND VALUE GENERATED continued

A ‘value of monitoring’ calculation can be performed on these detections and put on a per turbine per year basis. The value does vary from site to site, but is generally driven by several factors:

- Combine crane and crew costs for multiple repairs in one deployment
- Reduce downtime by early notice of developing failure
- Reduce consequential damage with early uptower repairs instead of running to gearbox failure. With today’s repair technology this may include intermediate and planet stage repairs.
- Extend bearing life by grease flushing and repacking
- Extend gearbox life by derating until repairs are possible

Typical industry saving related to the above results are between $40-$80k for combining crane activity and reducing downtime, and $300k for preventing a blade failure. Using these values, the value of the monitoring for these 19 failures was approximately $1.75M, providing an ROI over 5:1.

TIMELINE FOR A MAIN BEARING FAILURE

In the timeline for a main bearing failure (or other bearing) there is ample opportunity to manage the cost of failure given the detection lead time. Figure 6 provides an example with a screenshot from Fleet Monitor™. The data from both the SCADA and vibration monitoring systems are processed by advanced diagnostic methods to generate health indeces that maximize early warning and reduce false alarms. Point A is where the site was first notified, Point B the first inspection and Point C the second inspection. After 14 months the bearing is still in service and the health of this bearing is being managed (by grease flushing) to extend the life. Notably the temperature health index, which incorporates advanced corrections for seasonal variations and site averages, does not provide any early warning - the bearing is not getting hot until it reaches a very poor condition.

Level	Alarm	Turbine	Sensor	Measurement	From	To	Class
	HSS gear alarm (3S1)	T17	Highspeed	FFT_3B_Tr	11/13/2015	11/13/2015	7
	Generator DE stator (3S1)	T17	Generator DE	FFT_5A_Tr	11/1/2015	11/1/2015	7
	Main bearing alarm (2D1)	T17	Main Bearing	Time_2A_Tr_D1S	6/7/2015	10/3/2015	7
	IMS bearing alarm (4D4)	T17	IMS	Time_4A_Tr_D4S	9/2/2015	9/2/2015	7
	Planetary stage alarm (1D1)	T17	Planet	Time_1A_Tr_D1S	6/22/2015	6/22/2015	7

Showing 1 to 5 of 5 entries

Main bearing alarm (2D1) - Main bearing inner race health index (D1) - T17 – OC7: 2.415 MW (m/s²)

Ⓐ Initial detection (Nov 2014) Ⓑ Inspection confirms bearing damage (Nov 2014) Ⓒ Follow up Inspection for Damage Progression (Sept 2015)

Figure 6 – Romax Fleet Monitor^{TM} providing over 14 months warning on main bearing damage. First detection at Point A. Inspection at Point B confirming significant spalling on the raceways and rollers. Re-inspected at Point C after monitoring engineers warn of recent rise in the health index.

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