Advanced Sensors and Monitoring & Diagnostics (M&D) for Gas Turbines

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Abstract

Advanced sensing and analytics are being used increasingly in power systems, to improve diagnostic and prognostic capabilities for expensive power generation equipment, increase performance and operability, estimate remaining useful life, and manage risk. A wide variety of technologies, from recent sensing technologies to advanced analytics, are being used by power generation equipment manufacturers, and utilities.

This talk will focus on sensor and monitoring & diagnostics (M&D) technologies for gas turbines. A case study in the development and field deployment of sensor and M&D technologies, covering the aspects of signal processing, feature extraction, anomaly detection, and real-world implementation issues will be described in detail.

Outline

- Principles of Monitoring & Diagnostics
- Case study of a real-life M&D application with advanced sensors for gas turbine compressor health monitoring
- Summary

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How M&D fits into the big picture

Sensors, M&D/PHM & Analytics provide data that enables new products & services … and generate revenue over the life of the asset

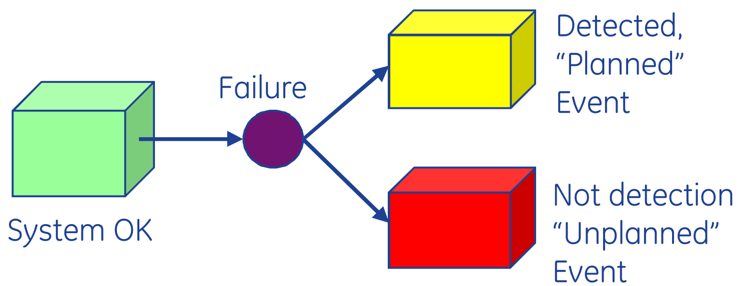
Uses of M&D

Requirements	Motivation, Goals & Business Impact
Failure Avoidance Parts life Extension Optimized Operation	❑ Prevent catastrophic failure ❑ Get closer to performance entitlement ❑ Support lifing models ❑ Design validation

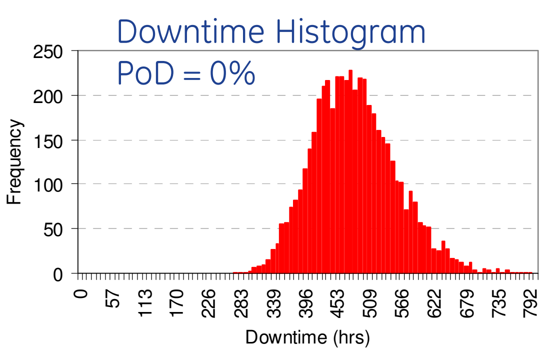
Impact of good detection capability on asset downtime

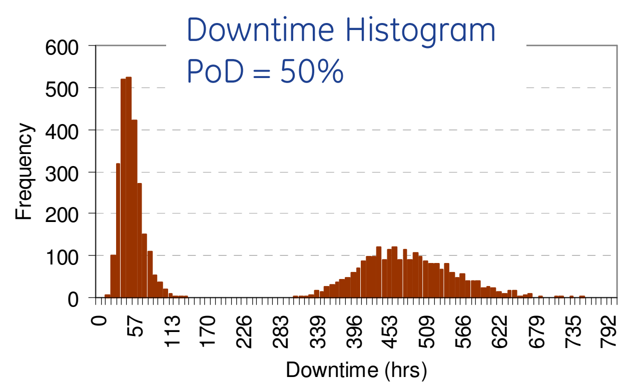
Example … we have a system with an onboard sensor / anomaly detection algorithm that detects failures in advance with some **Probability of Detection** (PoD). If failure indications are detected early on, associated risks, downtime durations & failure costs are typically much lower.

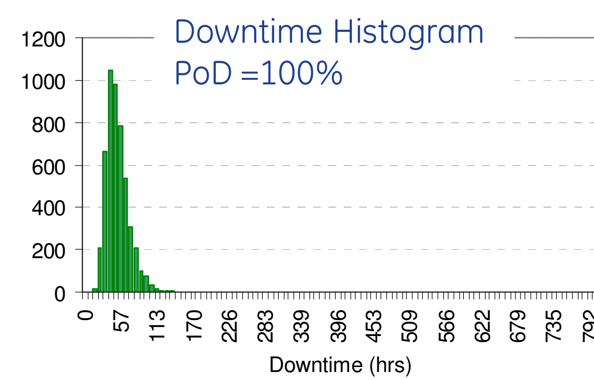
Simulation-based trade studies can be used to optimize the sensor suite (PoD, false alarm rate, time to detect, etc.) with the asset being monitored. This significantly improves reliability, reduces outage durations and reduces overall system operational risk.



Data & results for illustrative purposes only

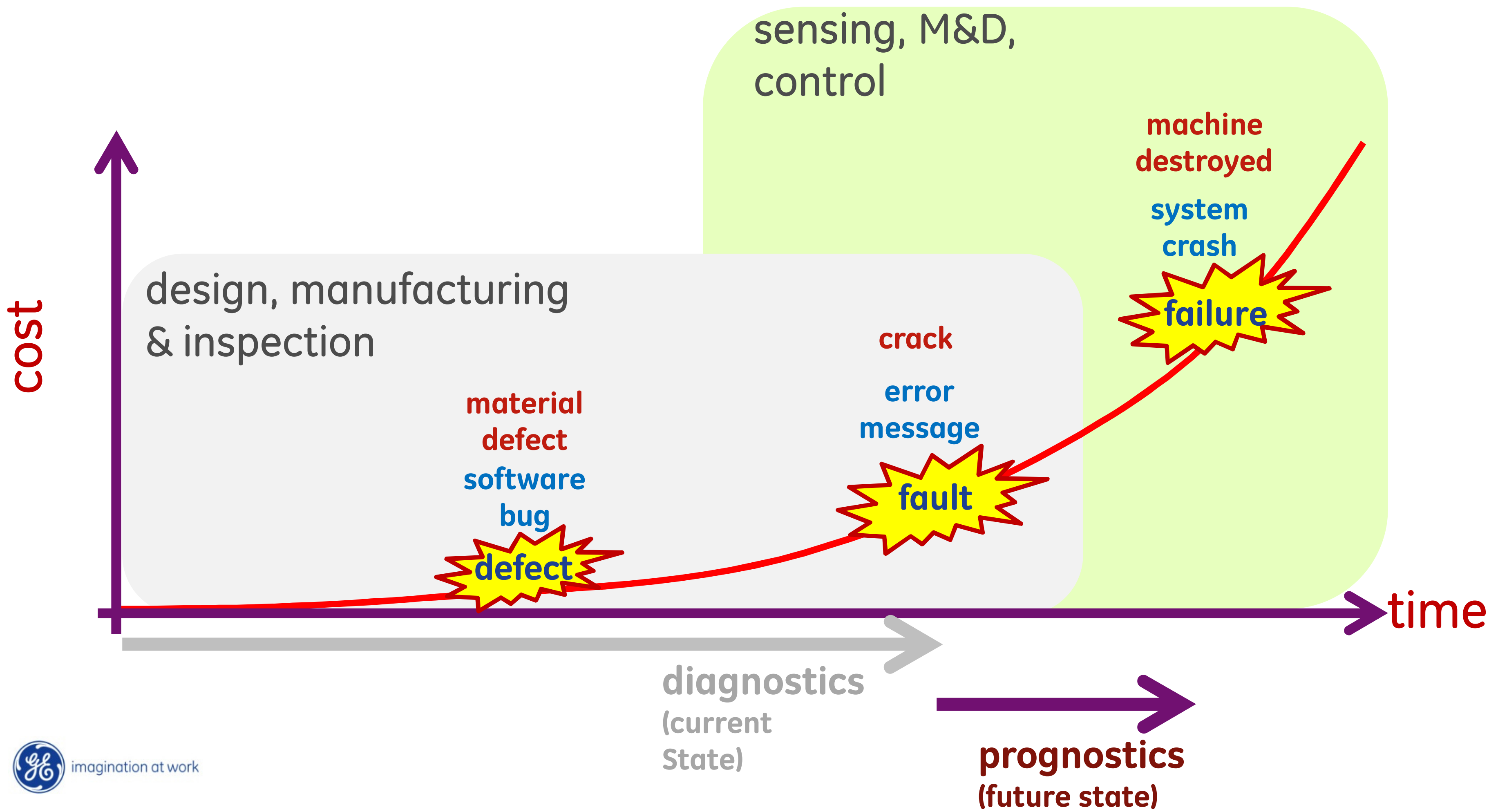




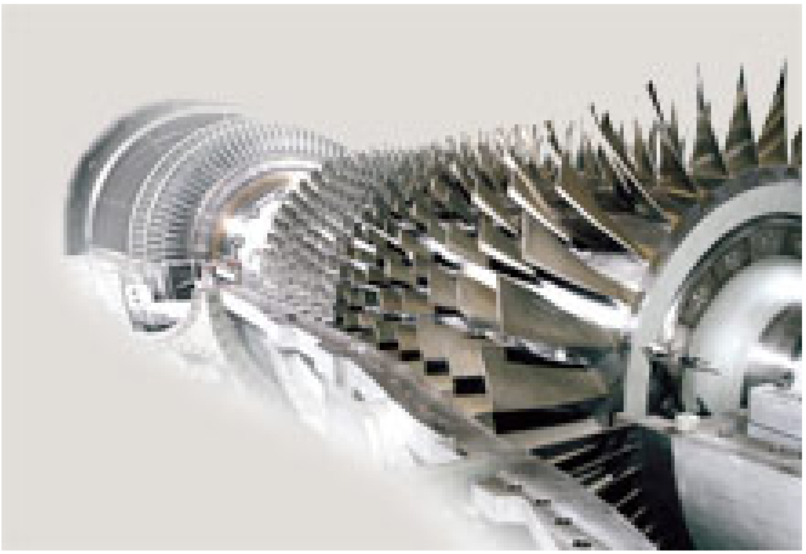


What is M&D?

A set of algorithms, processes & tools that allow monitoring the health of an asset – detect faults before they turn into failures.

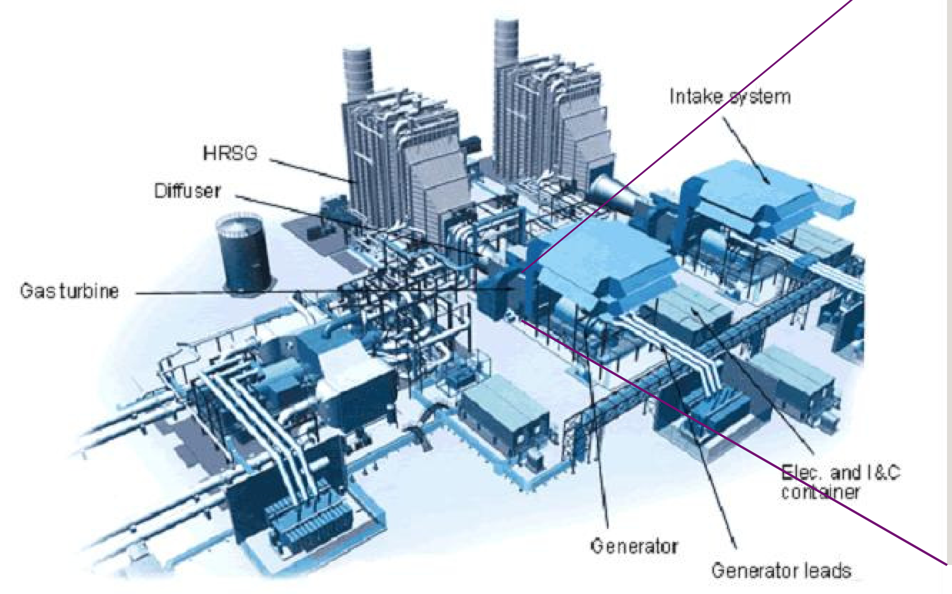


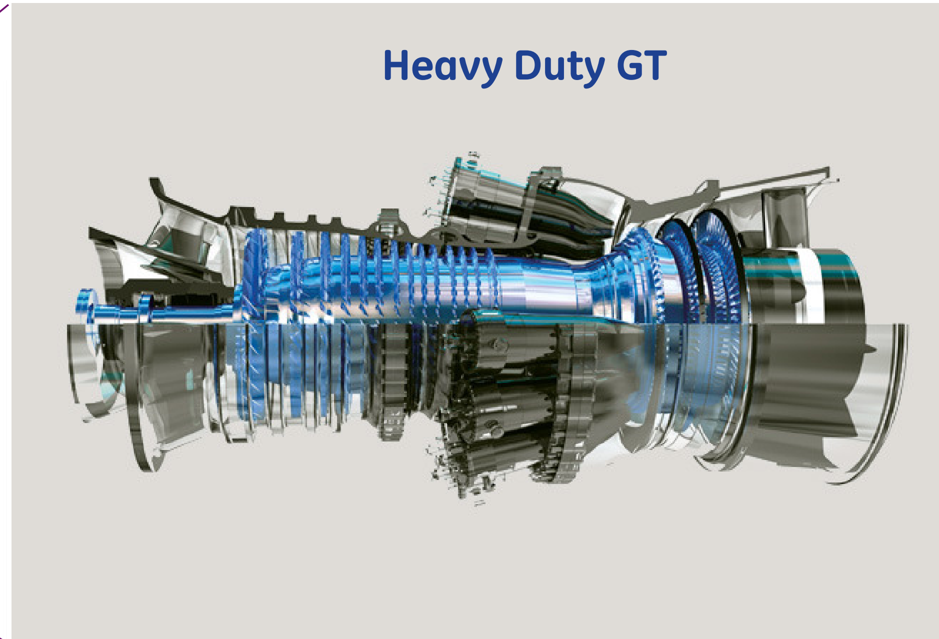
Preventable failures via M&D



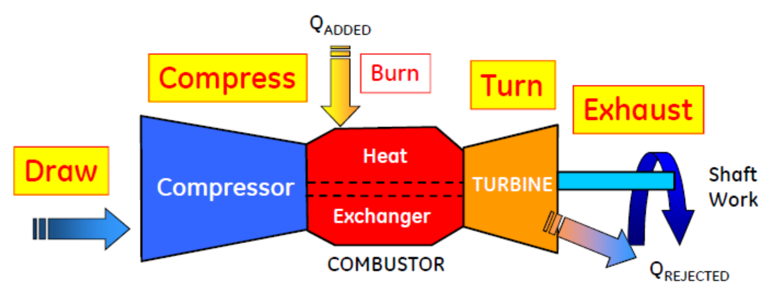
example of a gas turbine compressor blade liberation
followed by extensive secondary damage

Background on Combined Cycle Power Plants



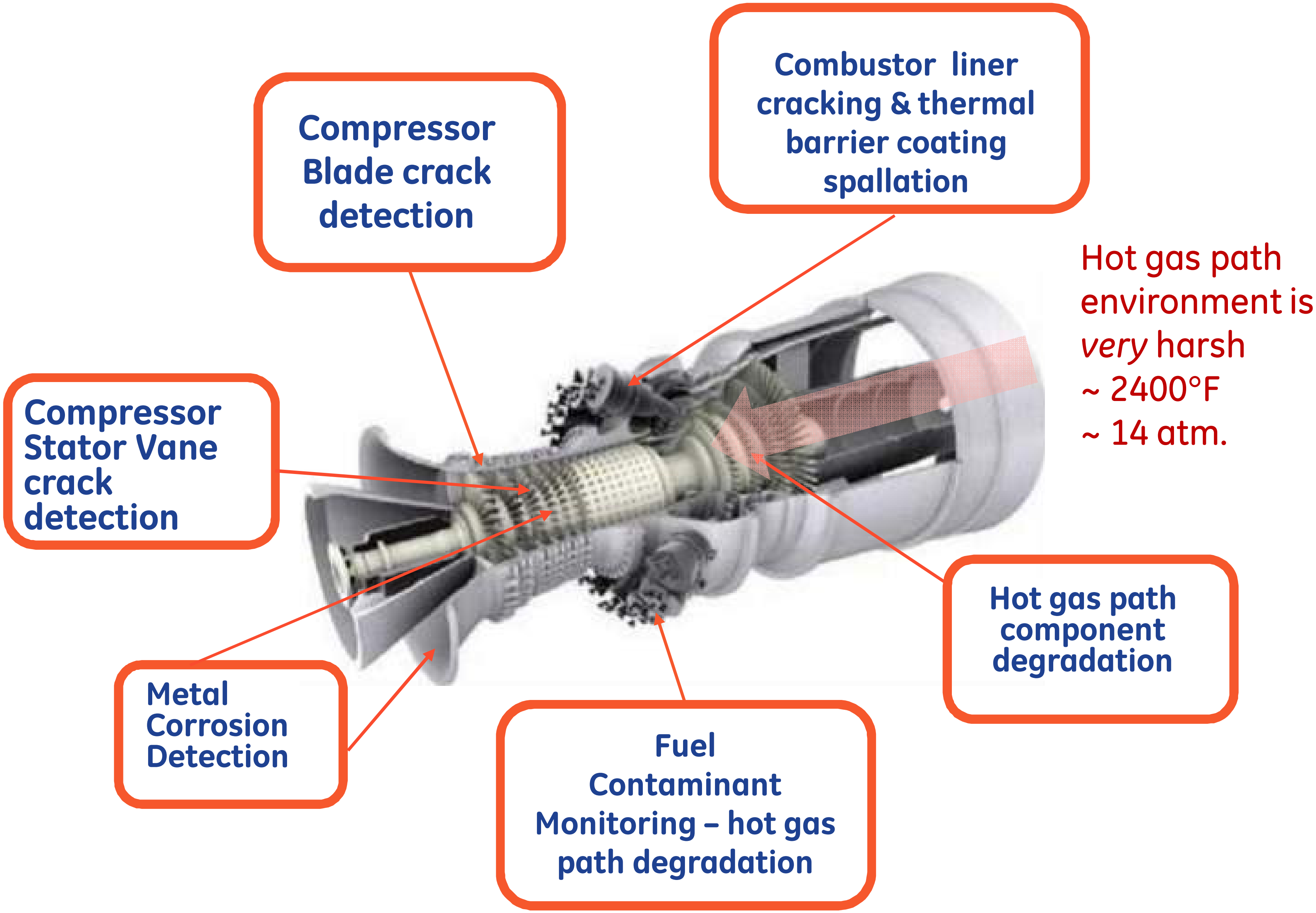


Simple cycle operation: 211 MW
Combine cycle operation: 632 MW
Sufficient to power 250,000 homes



Principles of GT Operation

GT Monitoring Opportunities



Design of an M&D system

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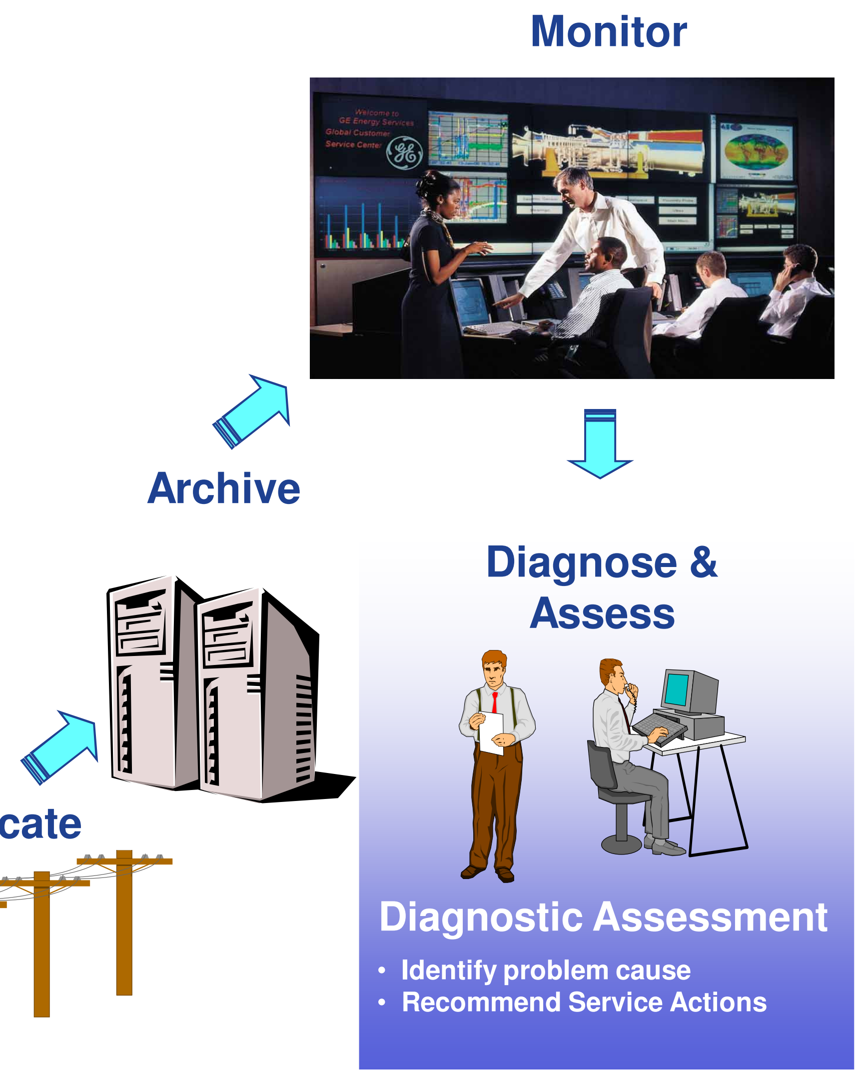
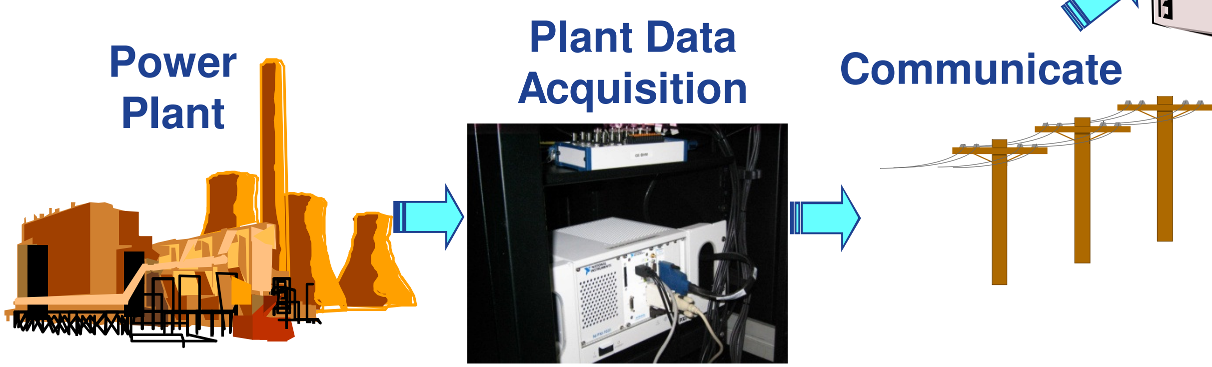
Remote M&D Architecture

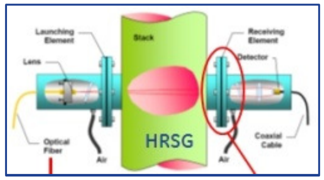
- Collect data from asset
- Process locally; Transmit data remotely over network/internet
- Archive, process more & visualize
- Run anomaly detection algorithms
- Validate and escalate



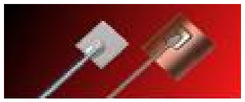


Sensing is the fundamental enabler of an M&D system

gas properties



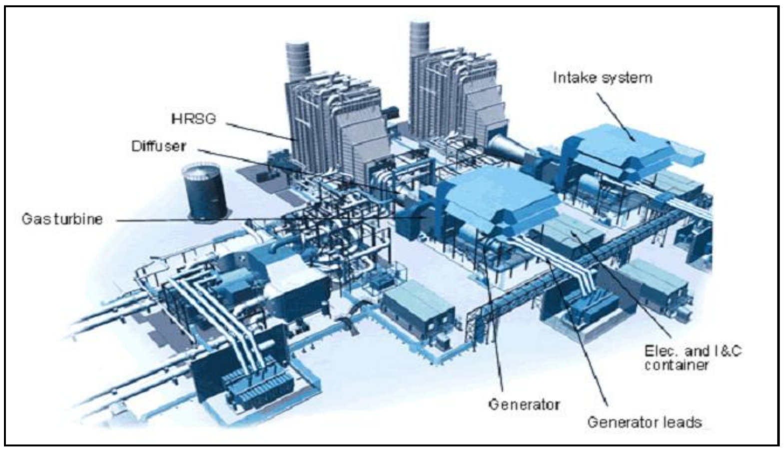
strain



position

plant
& turbine
controllers

flow



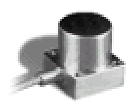
pressure

other
assorted
data
acquisition
systems

temperature

level

speed

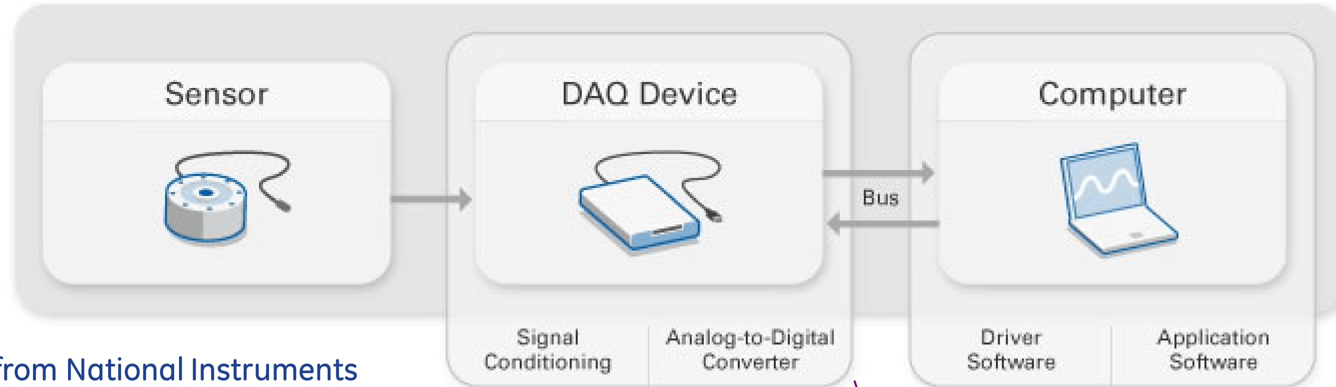


acceleration

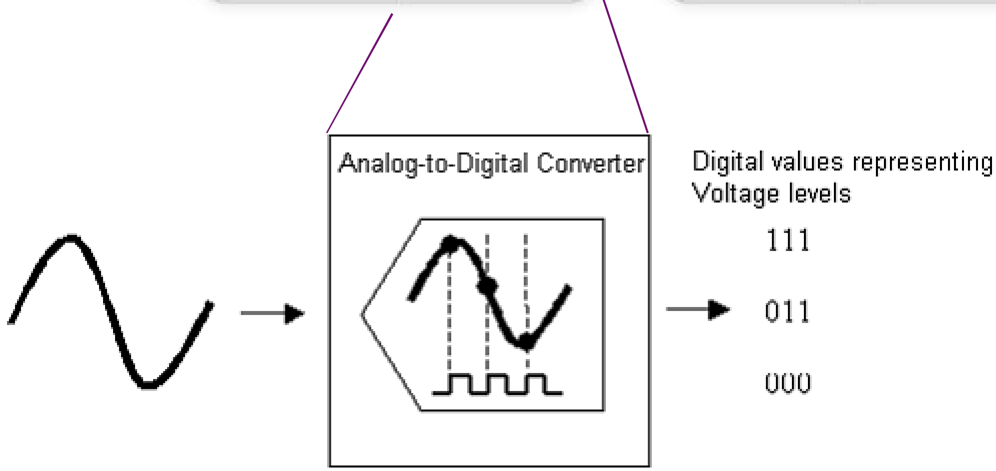
Sense

Acquire

Data acquisition & pre-processing



Images from National Instruments



Analog-to-Digital Conversion is the key first processing step; Translates the analog real-world to the digital world of the computer

Feature extraction & Anomaly Detection – major approaches

- **Statistical Methods:** various standard statistical measures, such as higher order moments of key parameters, moving statistical calculations, clustering and pattern recognition

- **Time Series Analysis:** time evolving nature of the major monitored parameters

- **Deviation from expected values:** track for deviations from set-point for failure modes and incipient failures detection

- **Model based methods:** increasing differences between models and observed values can give insights into impending failures and isolation using appropriate classification models

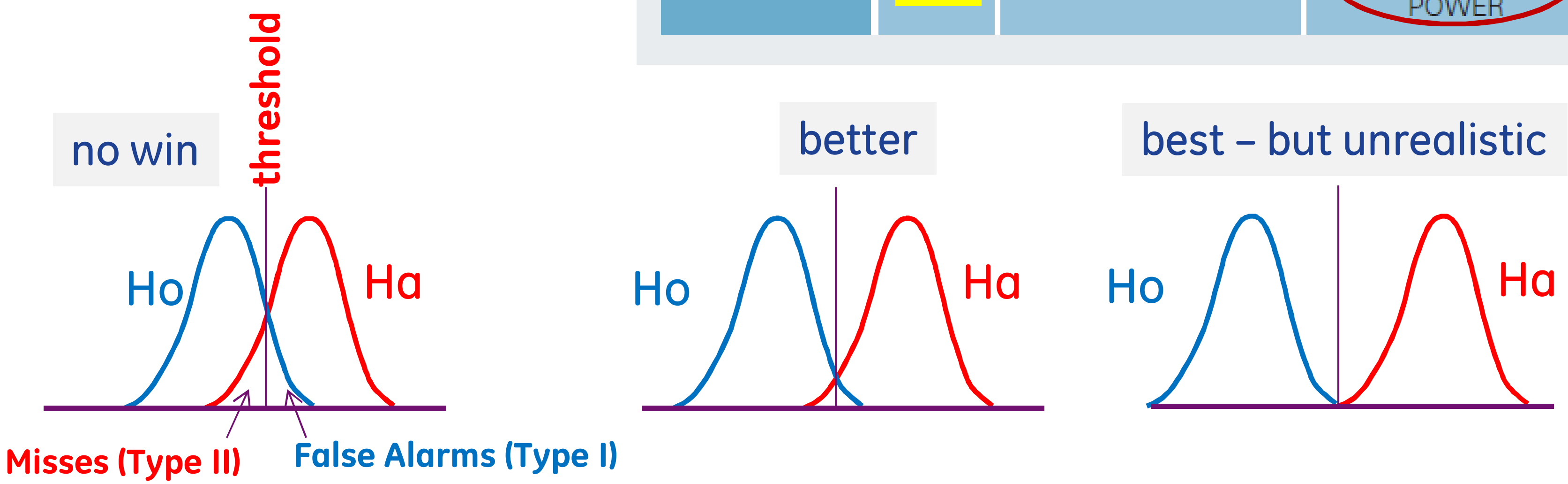
Alarming – threshold setting

- Threshold development is critical
- Hypothesis testing (False Alarms/Misses) – a key M&D concept
  - most real-world anomalies are not discretely separated, they overlap
  - need to make decisions with overlapping distributions between True and False

Ho : Null Hypothesis (good)

Ha : Alternate Hypothesis (bad)

		Decision	
		Ho	Ha
Truth in the population	Ho	CORRECT $1 - \alpha$	TYPE I ERROR α
	Ha	TYPE II ERROR β	CORRECT $1 - \beta$ POWER



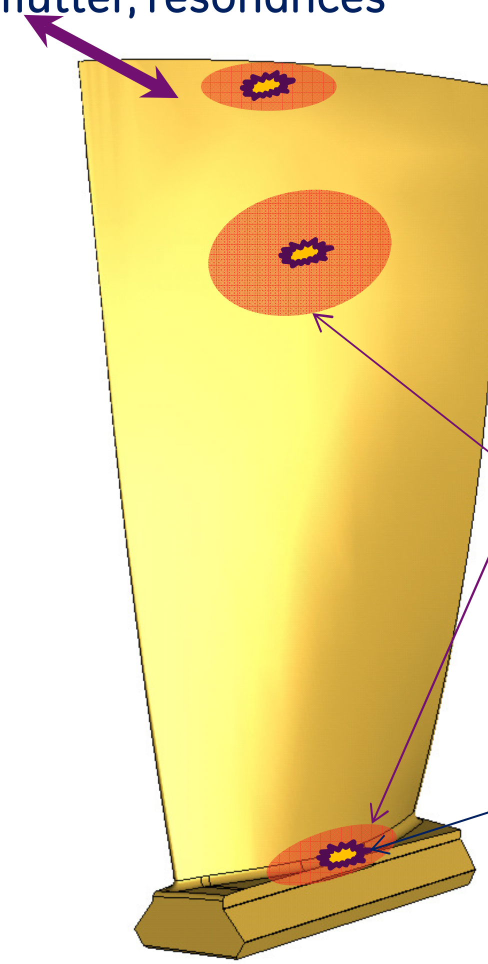
select features to maximize separation – key algorithmic challenge

Case Study

Compressor Blade Health Monitoring (BHM)

Typical failure drivers & mechanisms for turbine blades

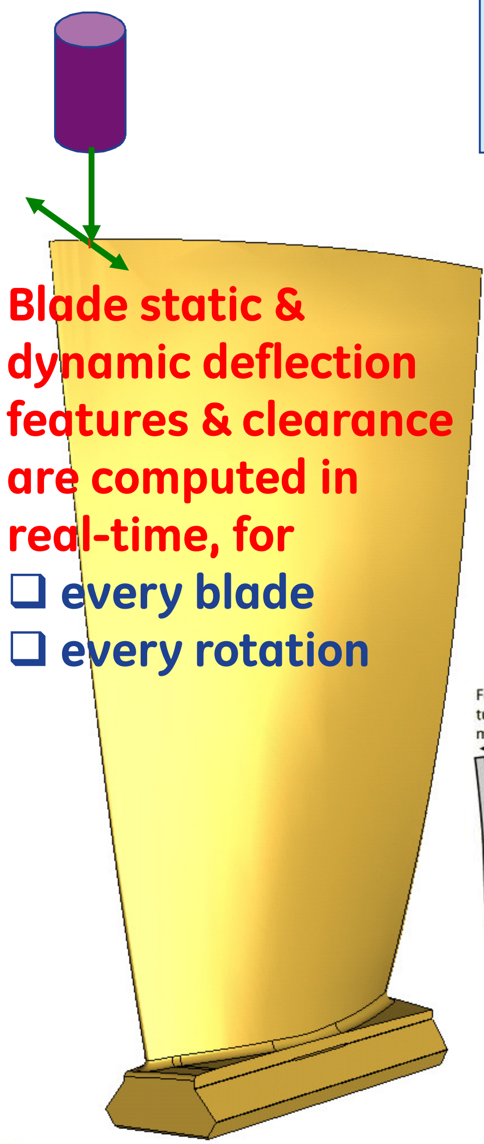
- ❑ High cycle fatigue (HCF)
  - ➢ Normal corrosion can initiate tiny pits in metal
  - ➢ Continuous flexing of blades during operation can grow cracks from pits (high cycle fatigue)
  - ➢ When a crack gets large enough, the centrifugal force can pull blade apart (liberation)
- ❑ Foreign Object Damage (FOD):
  - ➢ Debris gets sucked in and damages blades
- ❑ Rubs
- ❑ A liberation could cause significant secondary damage -> millions of dollars



typical gas turbine compressor blade

M&D Approach– model driven diagnostics

sensor

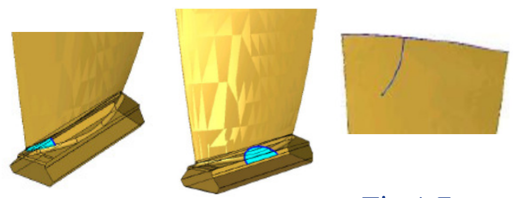


Blade static & dynamic deflection features & clearance are computed in real-time, for

- **every blade**
- **every rotation**

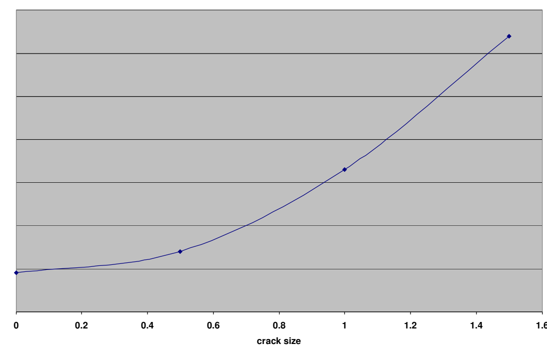
model based expectations of feature changes (validated via seeded fault tests)

FE crack models



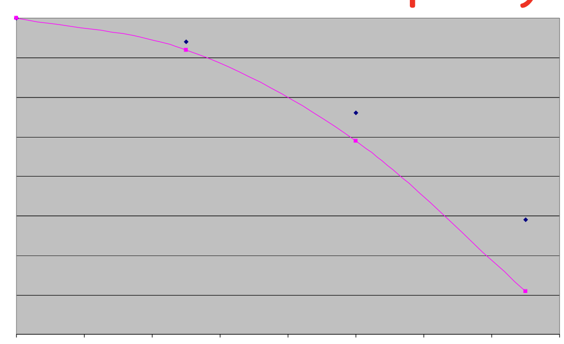
Expected signatures

Static deflection

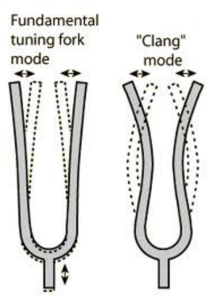


Crack size

Resonant Frequency Detuning



Crack size



Resonance detection: commonly used structural health monitoring feature

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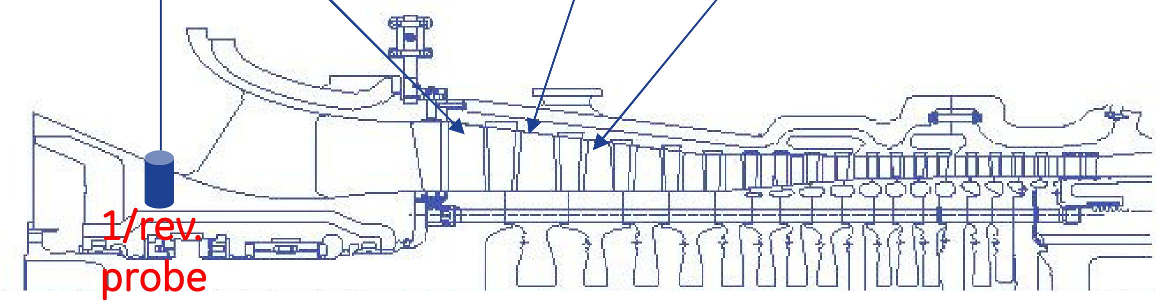
Monitoring System Overview

7.5 Mbytes/sec

R0 Blades

R1 Blades

R2 Blades



1/rev. probe

Data Acquisition System

A/D converter

Blade tip timing calculation

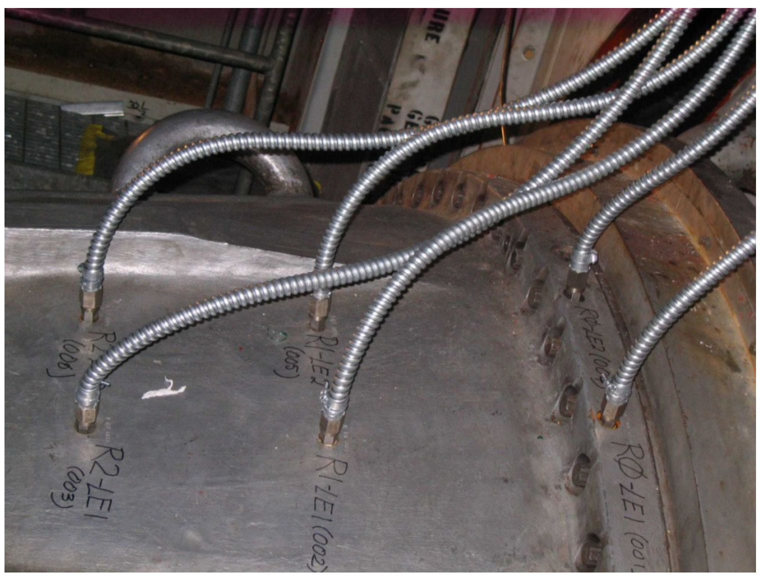
On-site (plant)

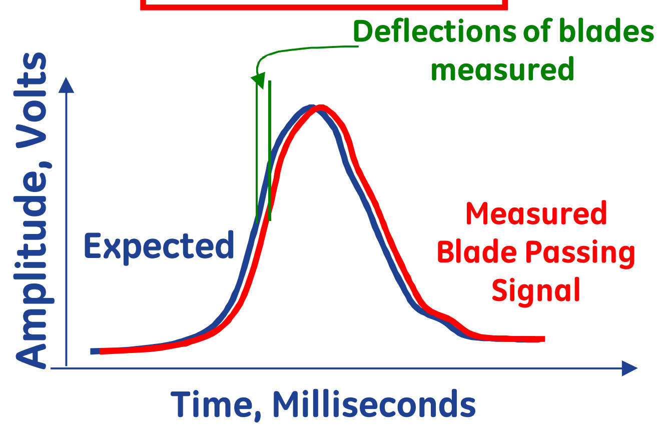
400:1 data reduction

Off-site

Blade Vibration Analysis

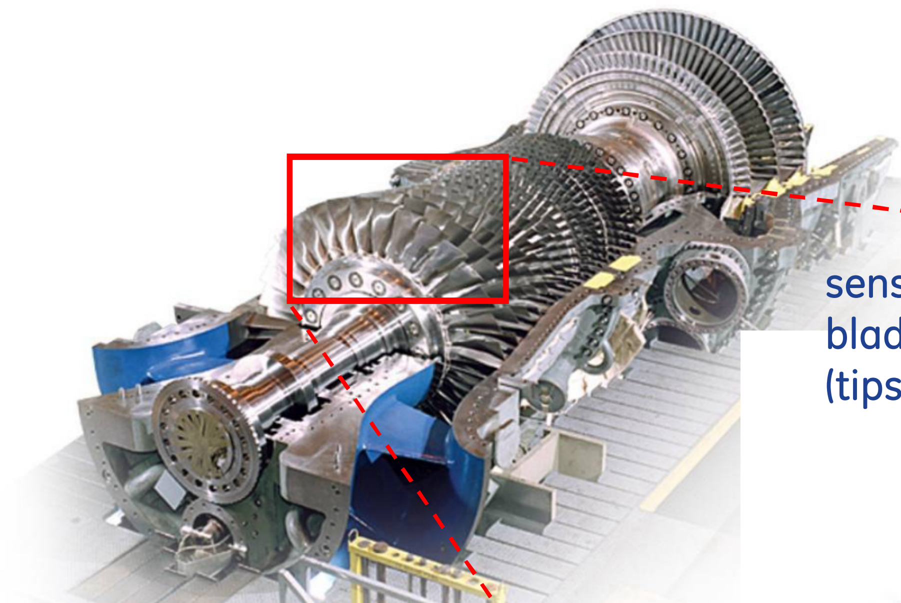
blade probes installed on compressor casing



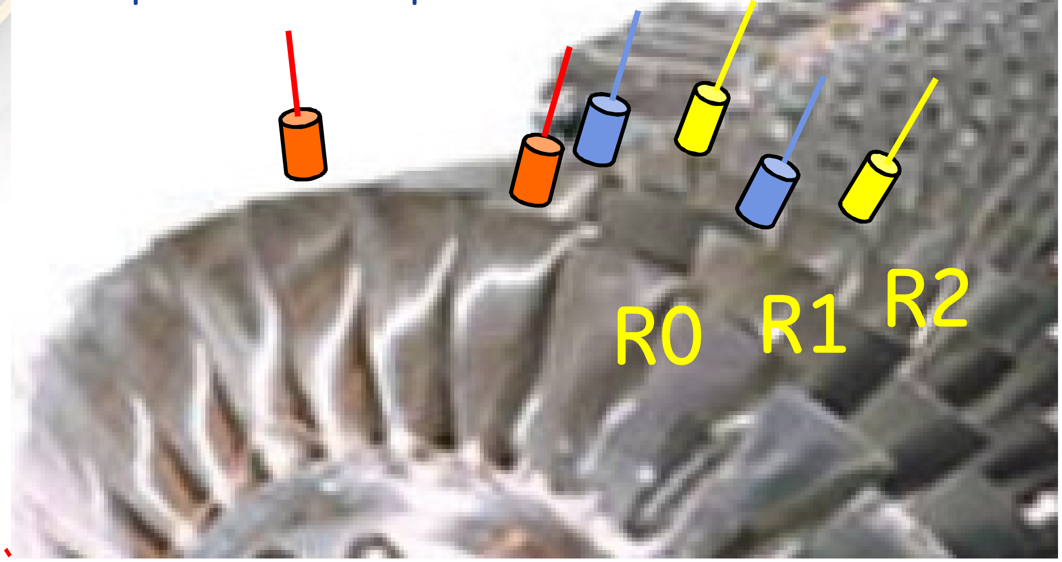


Sensing blade position

passive reluctance
probe



sensors monitor
blade passage in real-time
(tips move near speed of sound)



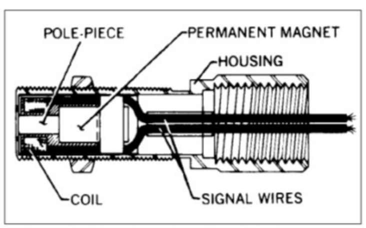
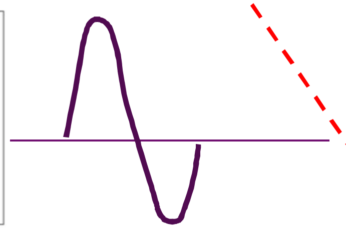
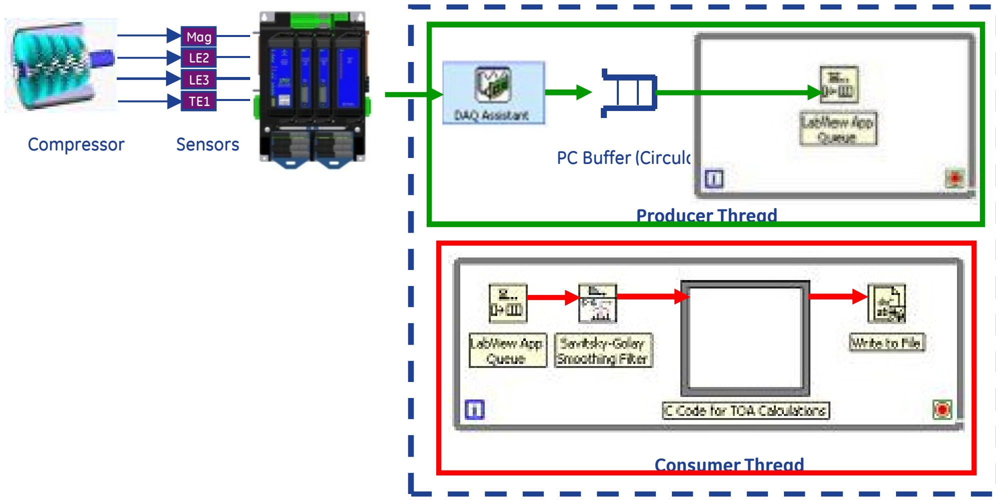


Figure 1 - Internal configuration of typical sensors.

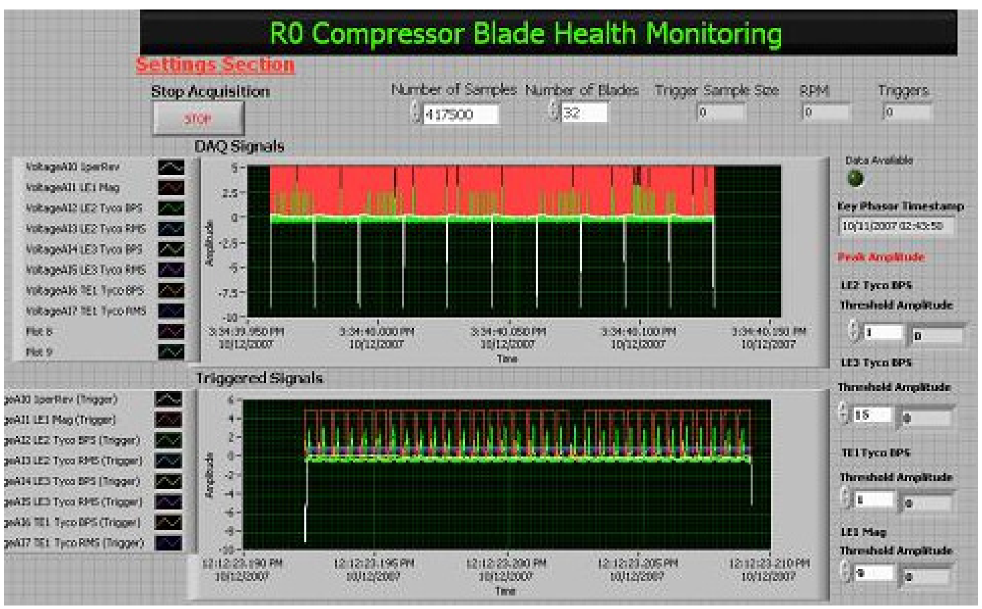


induced voltage
by blade passing - Blade
Passing Signal (BPS)

DAQ Data Processing Architecture



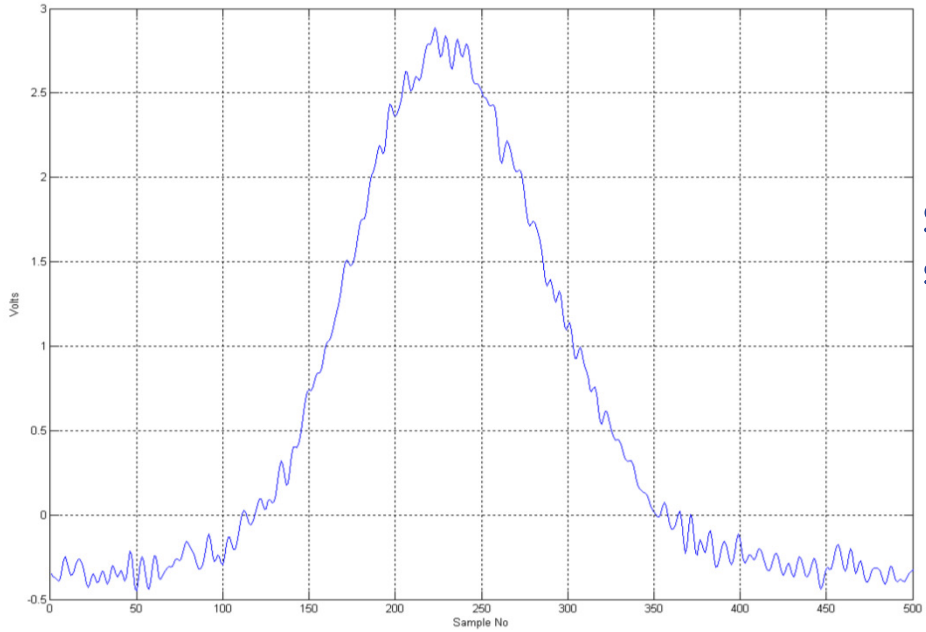
DAQ



Pre-processing:

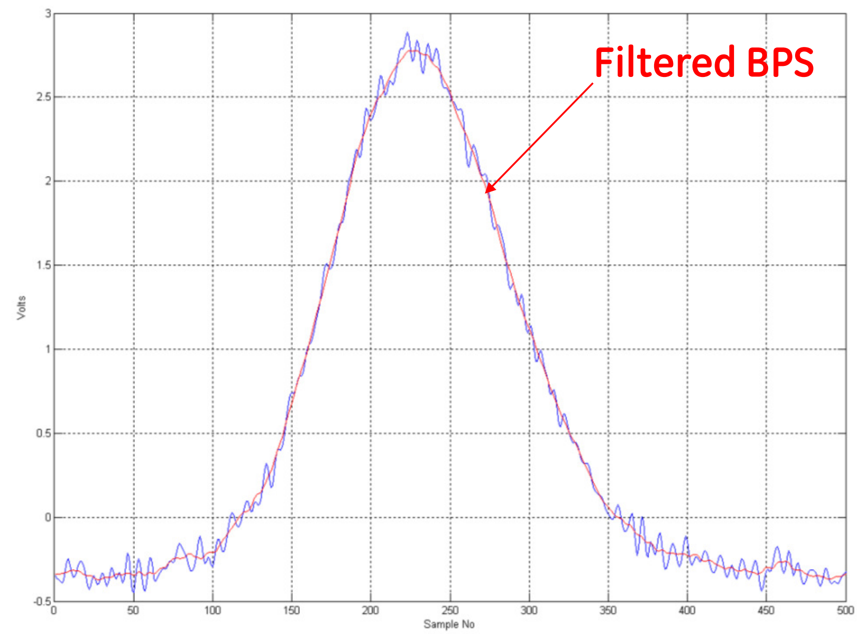
- **Digitize blade passing signal**
  (> 300 kHz)
- **Filter signal**
- **Process and find the Time-of-Arrival (TOA) of each blade in real-time (every 500 microseconds)**

Time-of-Arrival Calculation



Single raw BPS from a sensor

Smoothing filter applied (red trace) -based on a moving window polynomial regression



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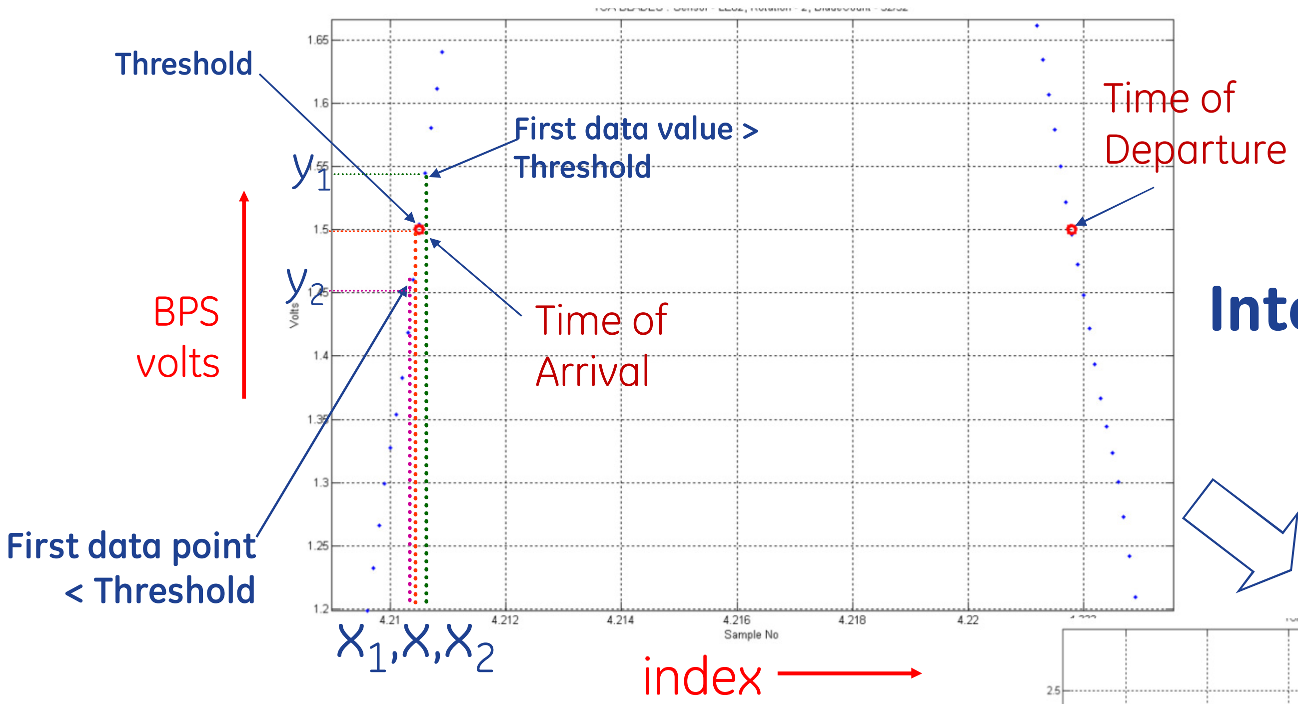
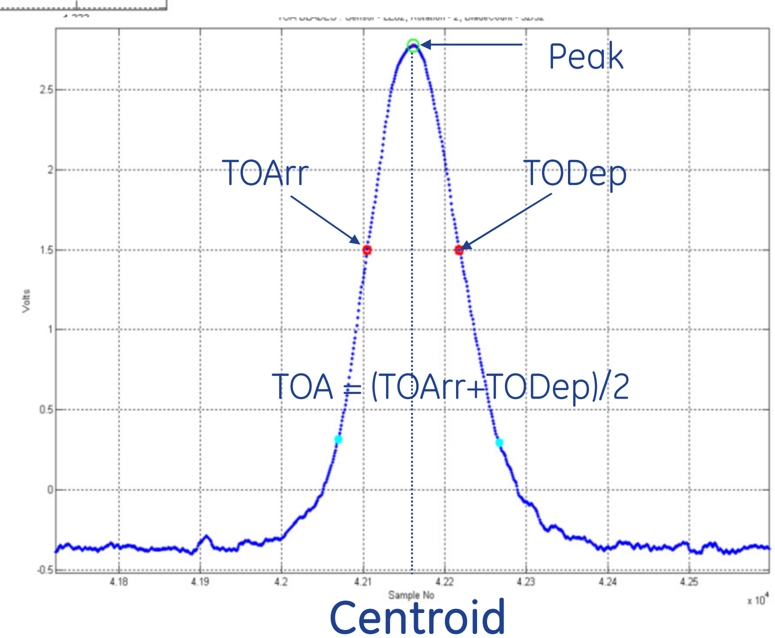
TOA calculation - Interpolation & Centroid Calculation



Interpolation



- **Time of Arrival/Departure is measured in terms of the A/D sampling index count.**
- **Algorithm=$(y_2-y_1/x_2-x_1)=(y-y_1/x-x_1)$. Find X for Y=1.5 volts (example).**
- **Interpolation needed to reduce quantization error on the DAQ A/D and any residual noise.**

Blade Time of Arrival (TOA)

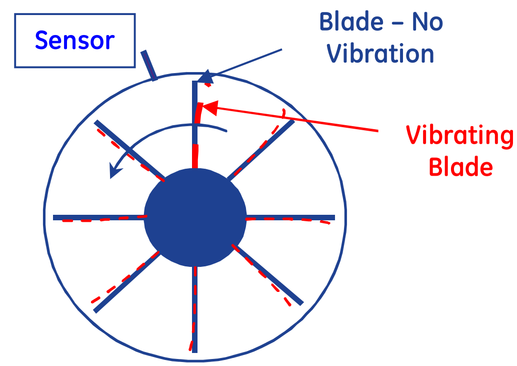
$$TOA_{meas} = TOA_{expect} + \delta_{static} + \delta_{vibration} + \varepsilon$$

Measured TOA | **Expected TOA** | **Static Deflection** | **Vibration** | **Noise**

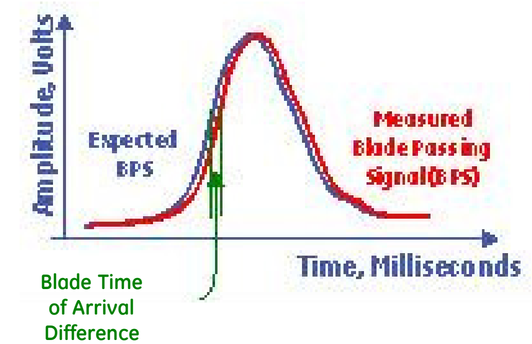
Expected TOA:
- Speed Variation
- Sensor and Key Phasor Relative Location

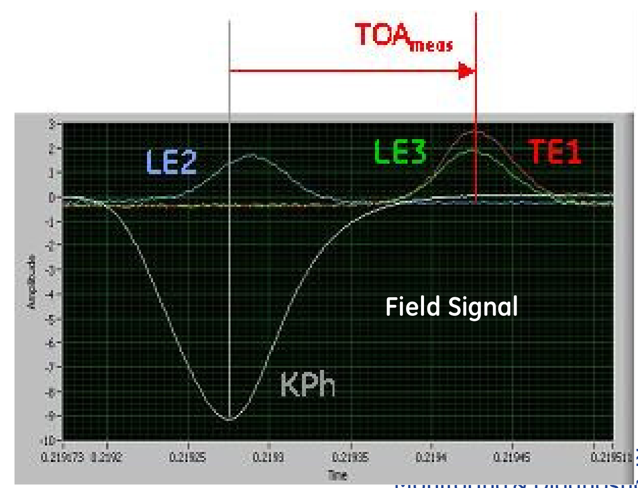
Static Deflection:
- Blade Geometry Variation
- IGV/Load Variation
- Blade Re-seating

Vibration:
- Asynchronous Vibration (Dynamic Deflection)
- Synchronous Vibration (Resonance Parameters)



Blade Delta TOA



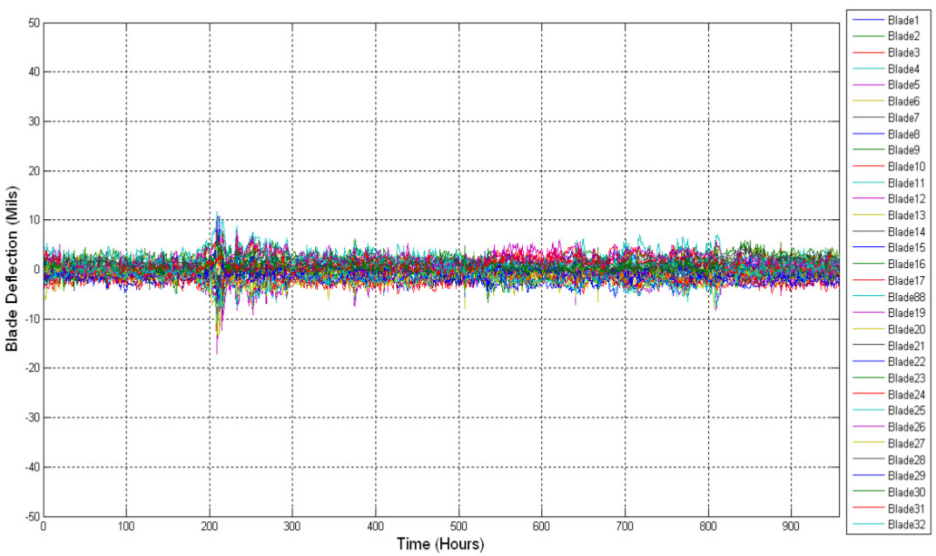


Key Blade "Health" Features

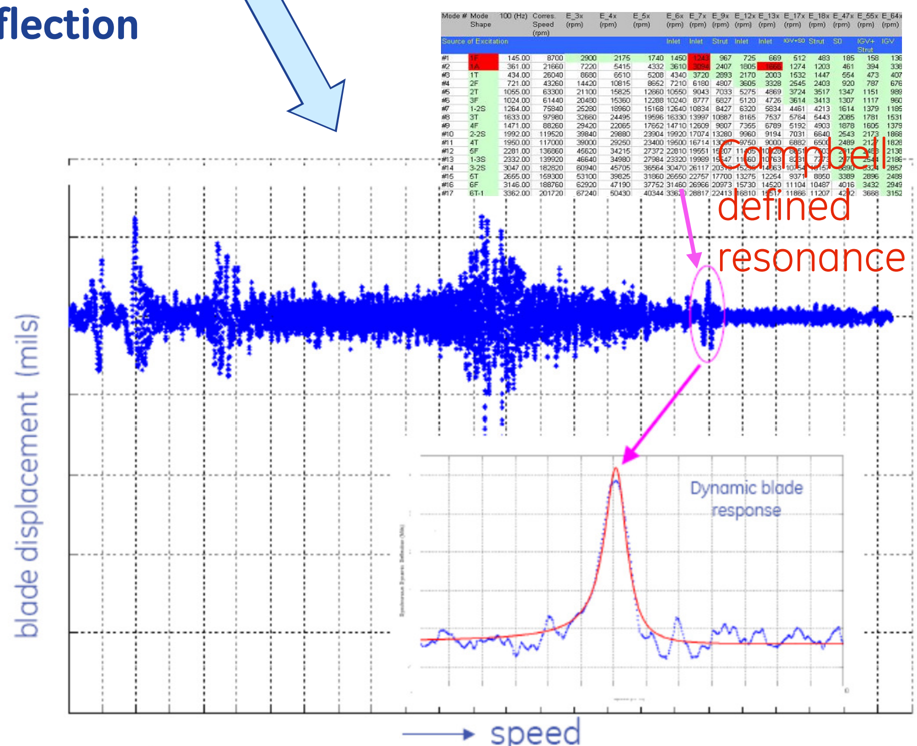
Blade Time-of-Arrival

$$TOA_{meas} = TOA_{expect} + \delta_{static} + \delta_{vibration} + \varepsilon$$

- TOA_{meas} → **Measured TOA**
- TOA_{expect} → **Expected TOA** — established at start of resonance and steady state condition
- δ_{static} → **Static Deflection**
- $\delta_{vibration}$ → **Vibration**
- ε → **Noise**



Static blade deflection tracked continuously



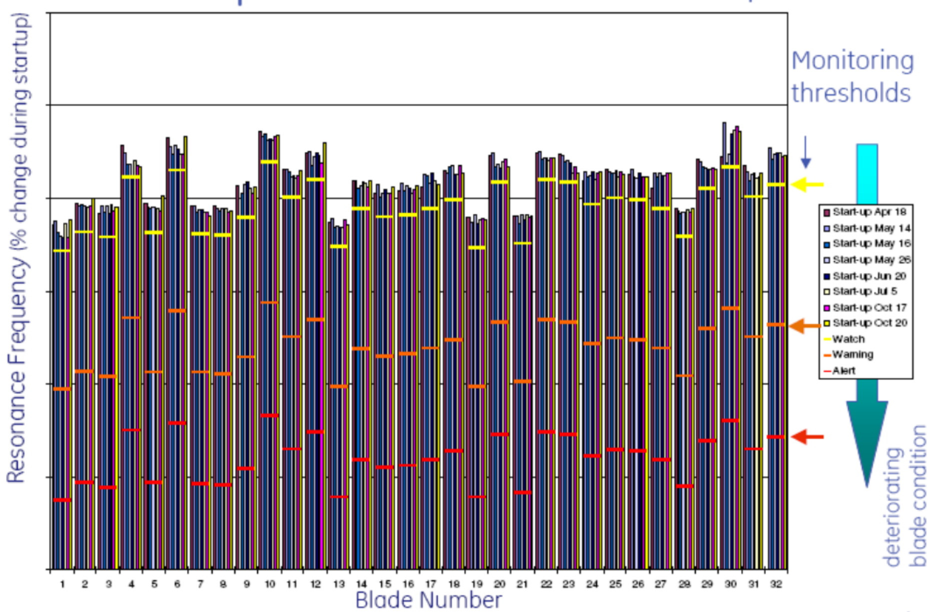
Dynamic blade response tracked on every start

Feature Trending & Thresholding

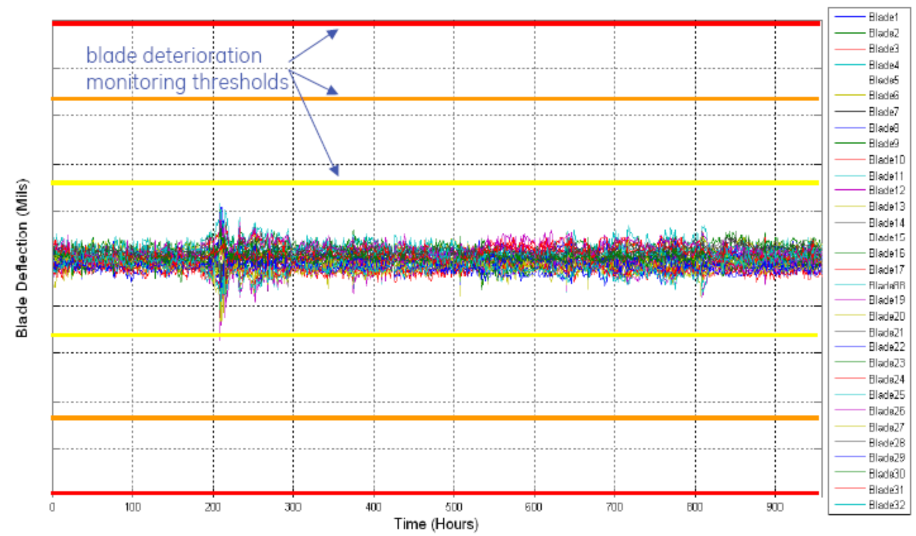
Resonances

Static Deflection

Blade Responses – trended over multiple starts



Blade Static Deflection Tracking at FSFL



Thresholds are established prior to monitoring

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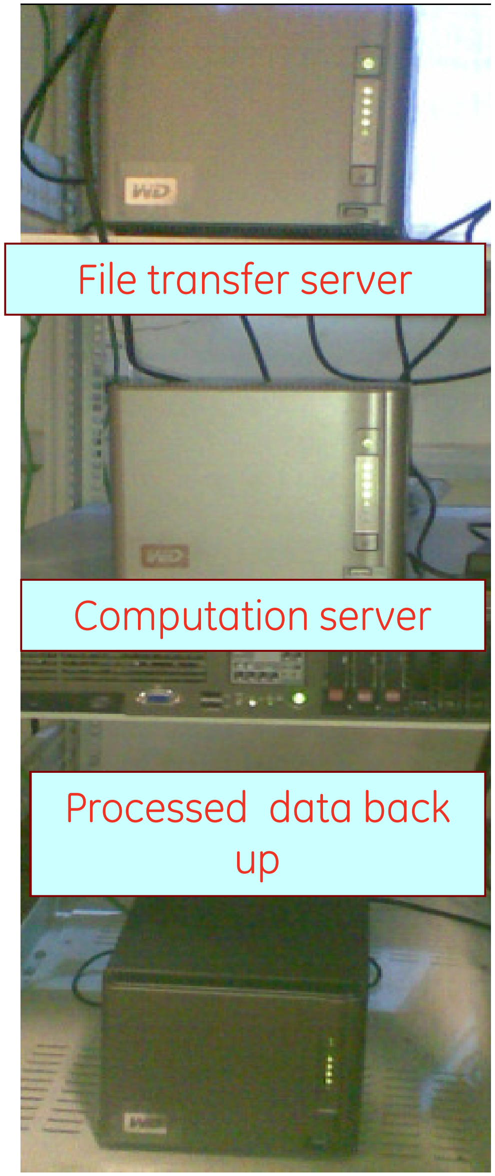
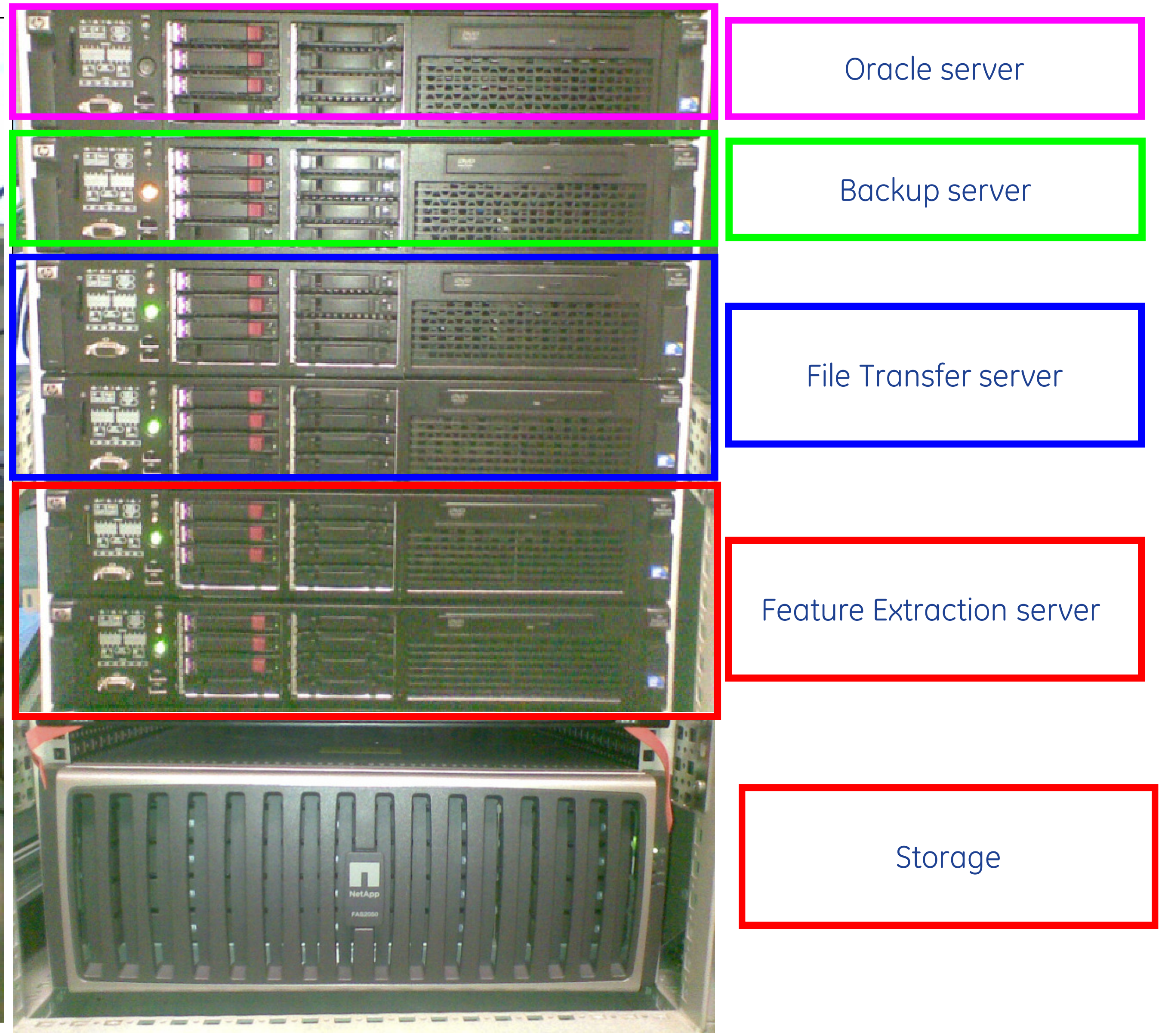
BHM 24x7 Computing Infrastructure

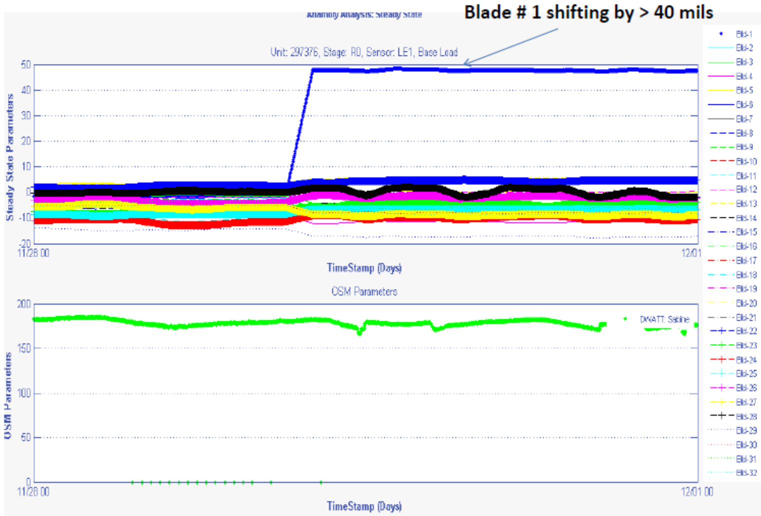




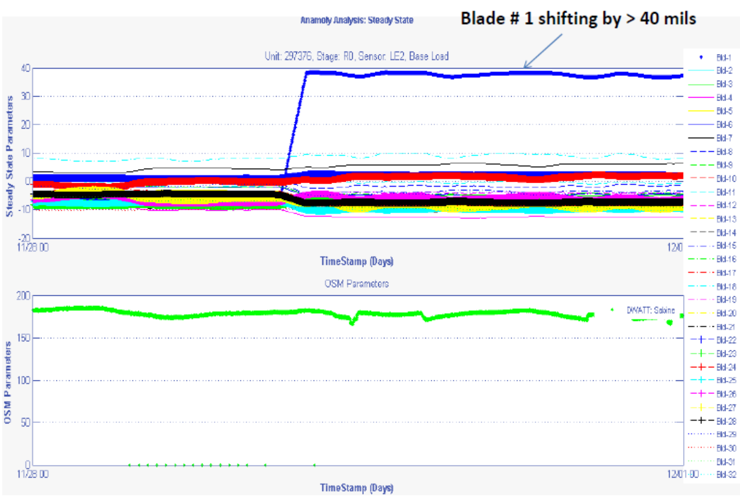
Field Validation - anomaly detection

BHM Signal Change

Static Deflection LE1



Static Deflection LE2



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Observed by BHM July 2011

- Shift observed in static deflection on R0 -Blade 1
- No change in vibration or performance
- Borescope inspection recommended

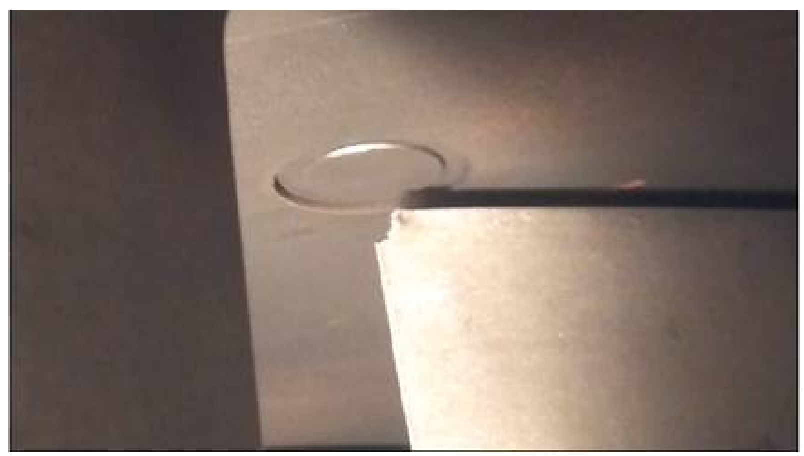
Findings

- Tip FOD on R0-1 confirmed

Conclusions

- FOD based tip damage
- Repairable damage

R0 FOD



M&D – the future…

- Use of M&D is increasing rapidly across many industries and applications
  - Sensors are getting smaller, cheaper, smarter and pervasive
  - Computing becoming cheaper exponentially
  - Wireless and portable visualization hardware (iEverything) will enable wider deployment
  - Provides significant payback

- The next frontier is Prognostics
  - Prediction of time to failure

- Analytics will play an increasingly larger role in processing the oncoming data deluge ("Internet of Things")