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A Comparison of Structural Health Monitoring and Condition Monitoring

Charles R. Farrar, Gyuhae Park, Kevin Farinholt
The Engineering Institute

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Abstract

This process of damage detection involves the observation of a system over time using periodically spaced dynamics response measurements, the extraction of damage-sensitive features from these measurements, and the statistical analysis of these features to determine the current state of system health. For long term monitoring, the output of this process is periodically updated information regarding the ability of the structure to continue to perform its intended function in light of the inevitable aging and damage accumulation resulting from its operational environments. Under an extreme event, such as lightning strike, damage detection procedures are used for rapid condition screening. This screening is intended to provide, in near real time, reliable information about system performance during such extreme events and the subsequent integrity of the system.

Damage identification is carried out in conjunction with five closely related disciplines that include Structural Health Monitoring (SHM), Condition Monitoring (CM), Non-Destructive Evaluation (NDE), Statistical Process Control (SPC), and Damage Prognosis (DP). Typically, SHM is associated with on-line, autonomous global damage identification in structural systems. CM is analogous to SHM, but addresses damage identification in rotating and reciprocating machinery. NDE is usually carried out off-line in a local manner with some *a priori* knowledge of the damage location. SPC is process-based rather than structure-based and uses a variety of sensors to monitor changes in a process, one cause of which can result from structural damage. However, many of the statistical monitoring tools developed for SPC have been adapted to SHM and CM applications. Once damage has been detected, DP is used to predict the remaining useful life of a system. There are no distinct boundaries between these various disciplines and in reality most damage detection methods applied to wind turbines will make use of some combination of these disciplines.

This presentation will focus on comparing and contrasting technical approached used for SHM and CM in the context of wind turbine applications. To do this comparison, the generic damage detection process will be posed in the context of a statistical pattern recognition paradigm. In this paradigm, the process can be broken down into four parts: (1) Operational Evaluation, (2) Data Acquisition and Cleansing, (3) Feature Extraction, and (4) Statistical Model Development for Feature Discrimination. Each of these four parts will be compared and contrasted in terms of how they are applied to SHM and CM. Specific aspects of the SHM and CM problems that enhance the damage detection process will also be discussed. The presentation will conclude by identifying outstanding technical challenges for both SHM and CM.

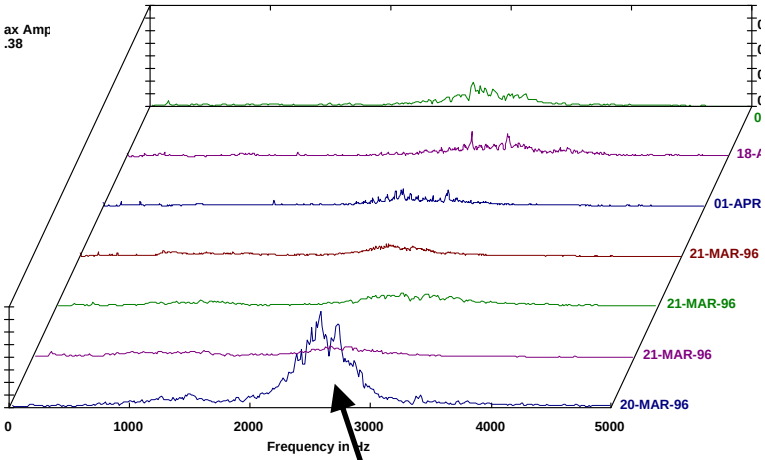
Damage Identification Methods

- **Damage Identification**
  - **Microscopic flaw/damage identification**
    - Used to develop fundamental understanding of material failure modes
  - **Incipient, macroscopic, material/component level damage**
    - Non-destructive evaluation (local, off-line inspection)
    - Wave-propagation-based **structural health monitoring** (more global, on-line)
  - **Component damage/failure – system level damage**
    - **Structural health monitoring**
    - **Condition monitoring (applied to rotating machinery)**
    - Health and usage monitoring systems (HUMS, Rotor craft)
    - Statistical process control (monitors system processes where damage can be one cause of loss of process control)
- **Damage Prognosis**
  - **Adds prediction of remaining life capability to SHM**

Vibration-Based Damage Detection

- Heuristic forms of vibration-based damage detection (acoustic) have probably been around as long as man has used tools.
- Most SHM and CM are based on some form of vibration monitoring.
- Developments in vibration-based damage detection are closely coupled with the evolution, miniaturization and cost reductions in FFT analyzers and digital computing hardware.
- The development of vibration-based damage detection has been driven by the rotating machinery, aerospace, offshore oil platform, and highway bridge applications.
- To date, the most successful applications of vibration-based damage detection has been for condition monitoring of rotating machinery.

Rotating Machinery Applications



Before Bearing Replacement

- Rotocraft Health and Usage Monitoring Systems (HUMS) :
  - 30-70 sensors measure usage data
  - recognises regime profiles, allows remaining life estimates
  - control study indicated 27% more missions flown with HUMS equipped fleet, & 10-30% less maintenance
  - **FAA and CAA approval**

SHM and CM are Problems in Pattern Recognition

The SHM & CM Process (Any Detection Problem)

1. Operational evaluation

   Defines the damage to be detected and begins to answer questions regarding implementation issues for a structural health monitoring system.

2. Data acquisition

   Defines the sensing hardware and the data to be used in the feature extraction process.

3. Feature extraction

   The process of identifying damage-related information from measured data.

4. Statistical model development for feature discrimination

   Classifies feature distributions into damaged or undamaged category.

- **Data Cleansing**
- **Data Normalization**
- **Data Fusion**
- **Data Compression**

(implemented by software and/or hardware)

Operational Evaluation: Wind Turbine Example

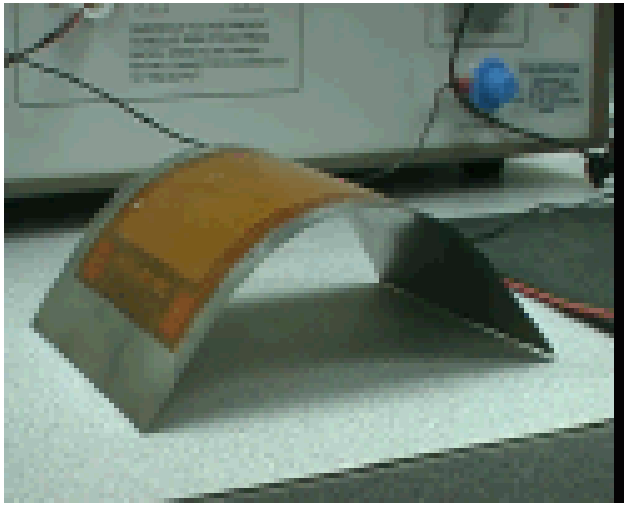
- Motivation for structural health monitoring is purely economic.
  - For an initial investment of about $1 -1.5 million/megawatt, then annual O&M costs using a 2% figure for 5 mw turbine are $100-150K/year.
  - 20 yr overhaul might cost 15-20% of the initial investment (in this example, $750 - 1500K).
  - **Defines allowable cost and service life of the SHM system.**
- Damage to be detected:
  - Delamination of composite turbine blades
    - **Need to define minimum area of delam that must be detected, expectable delam growth rates and critical delam area.**
  - Damage to gear box
    - Turns at 1000 rpm compared to 10 rpm of rotor
    - Shorter life compared to the rotor
- Environmental and operation constraints on the SHM System: rotating device, wind, rain, lightning, temperature, electromagnetic fields, offshore

Comparing CM and SHM Operational Evaluation

- **Need to define life safety or economic advantage provided by either CM or SHM systems**
- **Definition of damage:**
  - For CM there are a finite number of well-defined damage scenarios that are limited to a relatively small spatial region. (example: bearing failure). In most SHM applications the location of damage is not known.
  - Damage in CM occurs on a relatively short time scale compared to that of many structures where the degradation time scale may be longer than the maintenance engineer's career.
- **Operational evaluation:**
  - Measured inputs are usually not available CM and for many SHM applications
  - CM data are typically acquired during normal operation or during start-up or shutdown transients and often in well-controlled environments. Operational and environmental variability is much more significant for SHM applications.

SHM and CM Data Acquisition Systems

- **THERE IS NO SENSOR THAT MEASURES DAMAGE!**
  (and there never will be!!)
- **However, can't do SHM or CM without sensing**
- Define data to be acquired and the data to be used in the feature extraction process.
  - Types of data to be acquired
  - Sensor types, number and locations
  - Bandwidth, sensitivity (dynamic range)
  - Data acquisition/transmittal/storage system
  - Power requirements (**energy delivery**)
  - Sampling intervals
  - Processor/memory requirements
  - Excitation source (**active sensing**)
  - **Sensor diagnostic capability**



- **<u>CAN NOT</u> develop the sensing/processing system independent of the feature selection and statistical model development portions of the process.**

Comparing CM and SHM Data Acquisition

- Single channel FFT analyzer is adequate for most CM monitoring. (A single semiconductor fab engineer can monitor 2000 pieces of RM in one week).
- CM almost exclusively uses off-the-shelf sensing technology not specifically designed for CM
- Much more sensor development research associated with SHM applications. (e.g. wireless systems, fiber optics, optimal sensor placement)
- Active sensing used for SHM, CM is almost exclusively passive sensing
- Most *In situ* SHM system require significant capital expenditure and a significant maintenance budget. ($20 million for 1000 channels of data acquisition on Tsing Ma bridge in Hong Kong)

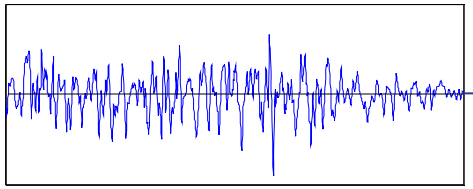
Feature Extraction

- Features are the quantities derived from measured data that are used to assess structural damage.
- Damage sensitive features fall into three categories.
  - Waveform or image comparison (primarily used for CM)
  - Model parameters
  - Residual errors between measured and predicted response.
- Want many samples of low-dimension feature vectors.
  - Numerous samples and low dimensional are necessary so that statistical distribution can be accurately quantified.
- Feature vectors can combine heterogeneous data types
  - dynamic response (e.g. first three modal frequencies) , environmental (e.g. temperature) , operational (e.g. vehicle speed)
- Must distinguish between a “feature” and a “metric”
  - A metric quantifies the difference in features

Example: Model Form Change

From healthy structure

$x(t)$



Time

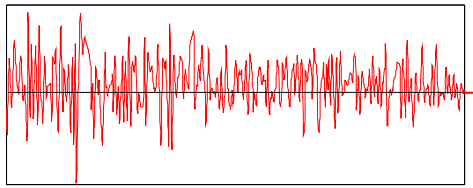
Estimate AR coefficients

$$x(t) = \sum_{i=1}^{n} a_i \, x(t-i) + \varepsilon(t)$$

$$x(t) = \sum_{i=1} a_i \, x(t-i) + \varepsilon(t)$$

From damaged structure

$x(t)$



Time

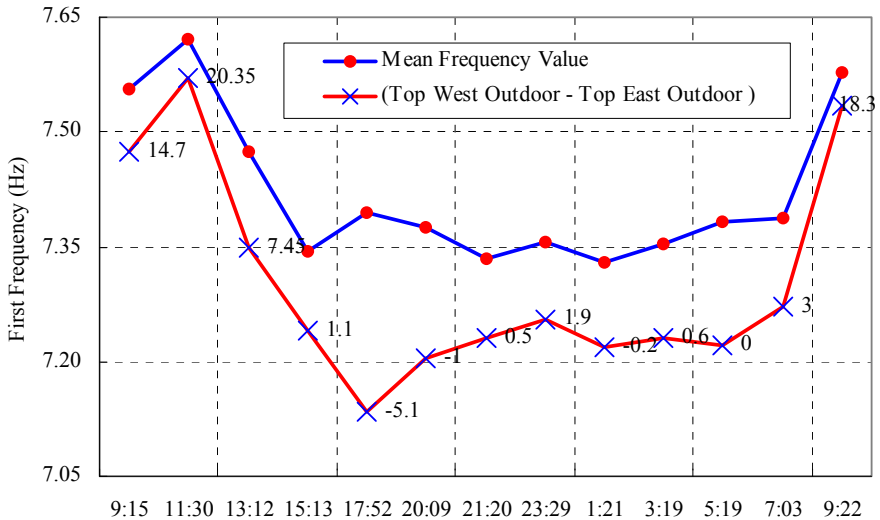
Estimate New AR coeff.

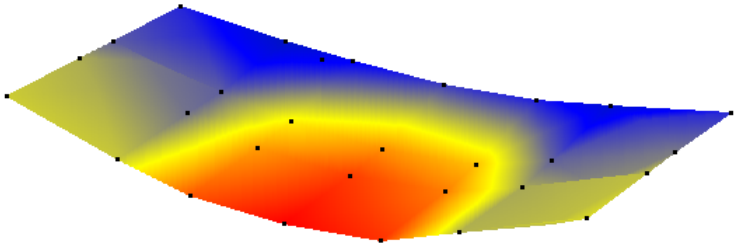
Comparing CM and SHM Feature Extraction

– **Feature Selection**

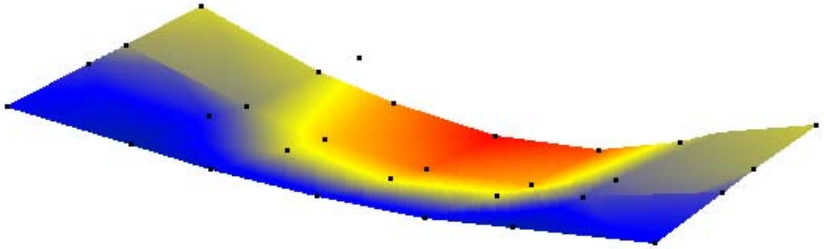
- Extensive data base correlating vibration features with specific types of RM damage.
- Data from damaged RM systems are often available for study.
- CM primarily makes use of waveform comparisons related to harmonic distortion.
- SHM makes more use of physical and time series models
- SHM derives features based on correlation between sensors
- SHM features incorporate spatial information

Data Normalization





First mode, 10 AM



First mode, 5:30 PM

Statistical Models For Feature Discrimination

- Supervised learning: Data are available from undamaged and damaged system.
- Unsupervised learning: Data are available only from the undamaged system.
- Three general types of statistical models for structural health monitoring:
  - Group classification (supervised, discrete)
  - Regression analysis (supervised, continuous)
  - Identification of outliers (unsupervised)
- Statistical models are used to answer five questions regarding the damage state of the system.

Statistical Model Building (cont.)

1 **Is the system damaged?**
- Group classification problem for supervised learning
- Identification of outliers for unsupervised learning

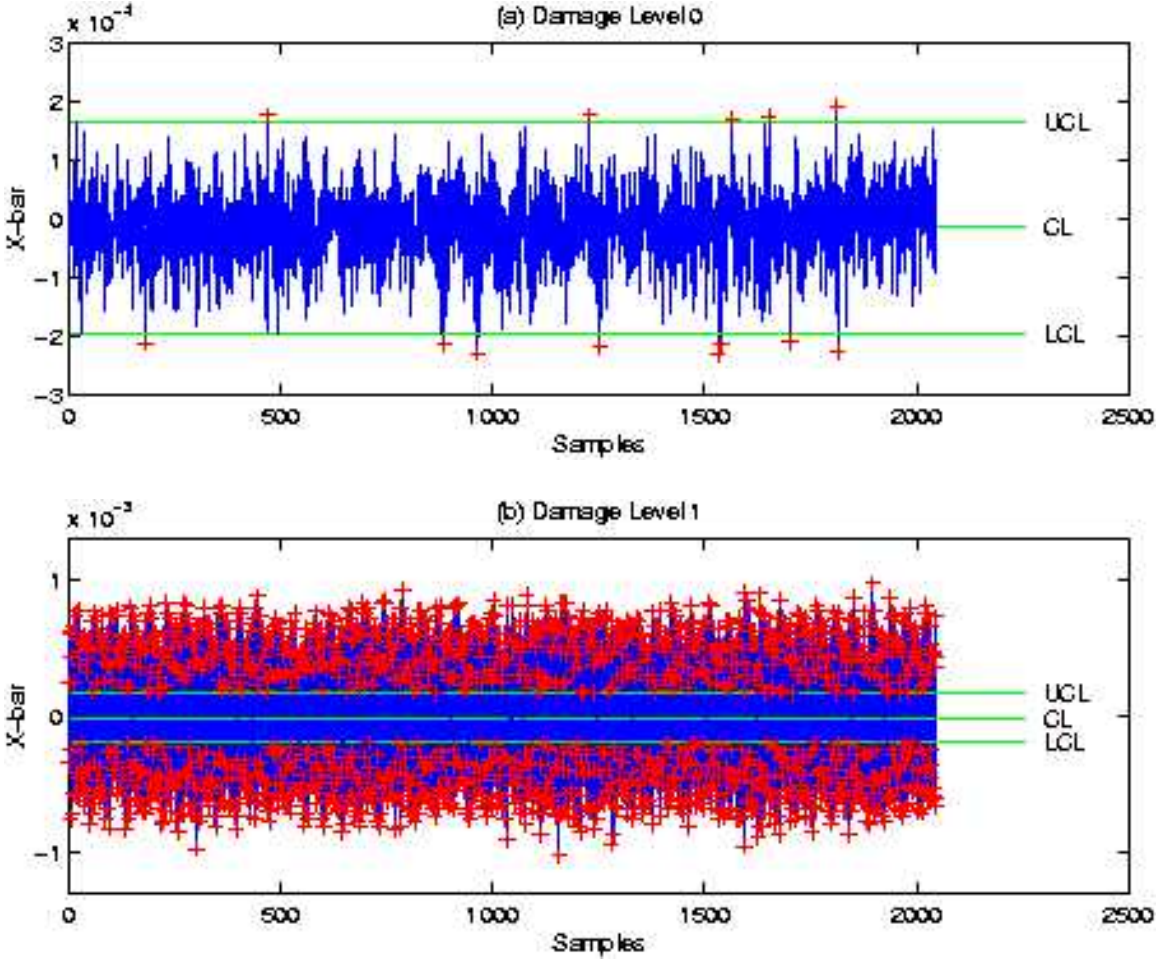
2 **Where is the damage located?**
- Group classification or regression analysis problem for supervised learning
- Identification of outliers for unsupervised learning

3 **What type of damage is present?**
- Can only be answered in a supervised learning mode
- Group classification

4 **What is the extent of damage?**
- Can only be answered in a supervised learning mode
- Group classification or regression analysis

5 **What is the remaining useful life of the structure? (Prognosis)**
- Can only be answered in a supervised learning mode
- Regression analysis

Control Chart Applied to Bridge Pier Data



Comparing CM & SHM Statistical Modeling

– **Statistical Model Building**:

- The CM literature reports many studies that investigate the application of statistical pattern classifiers to the damage detection process. Few applications of this technology to SHM studies.
- CM typically does not have the environmental and operational variability that is associated with SHM applications. (wind turbines are an exception)
- *Supervised Learning* can be applied to CM while *Unsupervised Learning* typically must be applied to SHM.
- CM often is performed on multiple nominally similar units that provide an extensive data base for classification process.
- SHM often applied to one-of-a-kind structures (civil eng. Infrastructure)

Summary and Concluding Remarks

- A statistical pattern recognition paradigm for damage detection has been proposed and applications to SHM and CM have been compared in terms of this paradigm.
- CM is mature and has made the transition from research to practice.
- SHM is still primarily a research topic
  - Data normalization
  - Damage location
- There are a lot of tools developed from other pattern recognition applications that are applicable to the SHM and CM problem.