Structural Health Monitoring Using
Statistical Pattern Recognition

Introduction to Structural Health Monitoring

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Outline

- Preliminaries
  - How we got started in this field
  - How we have evolved
  - Course evolution
- Course Philosophy
- Define Damage (Length scales, Time scales)
- Define Structural Health Monitoring
- Motivation for Structural Health Monitoring
- The Structural Health Monitoring Process
- Brief Historical Summary
- Operational Evaluation

Preliminaries

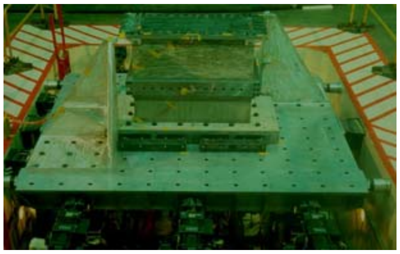
- Introduction of instructors
- Introduction of participants and their interests in SHM
- History of the course development
  - Originally developed for The Society of Experimental Mechanics
    - Offered prior to the 1997 International Modal Analysis Conf.
    - Developed with George James and Dave Zimmerman
  - Since then, the course has been offered 26 additional times
    - **U.S.** : Los Angeles, 2000; San Diego, 2002; Palo Alto, 1999, 2001, 2003, 2005, 2007, 2009, 2011, 2013; College Park, MD 2009; Tempe, AZ 2010; Snowbird, Utah 2013
    - **International :** Tokyo, 1998 (Japan Society for the Promotion of Science); Melbourne, 1998; Madrid, Spain 2000; Granada Spain, 2006; Tokyo, Japan 2010; Krakow, Poland 2011; Jeonju, Korea 2012, 2014
    - **Industry:** NASA Marshall 2004; BWXT Y-12 2004; Sandia National Lab 2006; Boeing 2006, 2009; U.S. Army Corps of Engineers, 2013, Ecopetrol, 2014
- What is new this time?
  - New lecture SHM System Design and Evaluation.
  - New lecture Review of Signal Processing

Course Philosophy

- Provide a brief history of structural health monitoring.
- Provide a systematic approach to structural health monitoring problems by defining the problem in terms of a statistical pattern recognition paradigm.
- Introduce participants to the components of this paradigm and demonstrate its application to various structural health monitoring problem.
- Provide an implementation strategy for this statistical pattern recognition paradigm based on a Bayes risk formulation rooted in detection theory.
- Show applications and discuss lessons learned.
- Show participants freely available software tools for implementing many techniques presented in the course.

How We Got Started (Circa 1985)

- We were involved in several experimental projects that required damage detection:
  - Seismic Category 1 Structures Program
  - Containment Buckling Program.
  - Seismic Qualification of Glove Boxes



How We Got Started (Circa 1992)

- 1992 I-40 Bridge Test was our first project that focused specifically on structural health monitoring

Our SHM Technology Evolution: Hardware & Software

- **1980s-Mid 90's** Inverse linear dynamic modeling approaches, DIAMOND Software, COTS accels/strain gages, first non-commercial sensors (ultrasonic interferometer)
- **Lates1990s** fiber optic sensing, **Statistical Pattern Recognition Paradigm**, operational & environmental variability, first literature review, first short course, Los Alamos Dynamics, LLC formed.
- **Early 2000s**, impedance method, guided-waves, wireless networking, Diamond II, data-driven modeling, formal statistical classification, first dynamics summer school, data normalization procedures
- **Mid 2000s**, wireless energy delivery, 2nd literature review, nonlinear system ID, LANL-UCSD Engineering Institute formed, fundamental axioms proposed, first UCSD graduate course in SHM
- **Late 2000s**, risk-based optimization, detection theory, PZT sensor diagnostics, , multi-functional sensor/actuator nodes, robotic platforms optimal excitation design
- **Early 2010s**, SHMTools software, advanced fiber optic sensing, scanning laser excitation/measurement systems, optimal sensor placement, image processing, info-gap robustness assessments, AUTOFEAD feature design/selection, haptic sensing interfaces, Acoustic Wavenumber Spectroscopy system

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Our SHM Technology Evolution: Applications

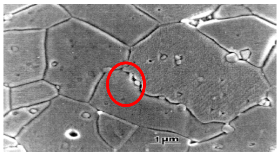
- **1980s-Mid 90's** Gloveboxes, Scale-model concrete reactor structures, containment structures, valve diagnostics, **I-40 Bridge**
- **Late1990s**, Alamosa Canyon Bridge, KNM Skjold Fast Patrol Boat, UCI concrete bridge column
- **Early 2000s**, Rim driven podded propulsor, roller coasters, composite-steel bolted joints, I-10 bridge, composite plates
- **Mid 2000s**, Composite UAV components, bolted steel frame structures, pipelines, hip prostheses
- **Late 2000s**, Alamosa canyon bridge, stiffened aerospace panels, SHM testbed structure
- **Early 2010s**, BAE fuselage section, composite UAV subsystems, wind turbines, telescopes, Navy HSV-2 Swift ship, Littoral Combat Ship-2, Modular SHM testbed structure, 737 Fuselage, Quadcopter

Definition of “Damage”

- **Damage** will be defined as changes to the material and/or geometric properties of a structural or mechanical system, including changes to the boundary conditions and system connectivity, that adversely affect *current or future* performance of that system.
- Implicit in this definition of damage is a **comparison** between two different states of the system.
- Examples:
  - crack in mechanical part (stiffness change)
  - scour of bridge pier (boundary condition change)
  - loss of tire balancing weight (mass change)
  - loosening of bolted joint (connectivity change)

Definition of “Damage”

- **Damage** is defined as changes to the material and/or geometric properties of a structural that adversely affect its performance.
- All materials used in engineering systems have some inherent **initial flaws**.
- Under environmental and operational loading flaws will grow and coalesce to produce **component level failure**.
- Further loading causes **system-level failure.**
- **The time and length scales of damage evolution (aging vs. extreme event) are diverse!**



•Inclusions at grain boundary

•Welded Connection

•Department Store Collapse

How Engineers and Scientists “Study” Damage

- **What causes damage?**
  - Material science (material aging and degradation processes)
  - Engineering analyses (exceeding allowable strength, deformation or stability criteria)
- **What can be done to prevent damage?**
  - Material science (new materials)
  - Engineering design strategies (design for inspectability)
  - Define operational and environmental limitations
- **Is damage present? (NDE, structural health monitoring)**
- **How fast will damage grow and reach a critical level?**
  - **NDE, Structural health monitoring**
  - Damage prognosis
- **How do we mitigate the effects of damage?**
  - Change operational parameters (e.g. speed of operation)
  - Maintenance and repair
  - Self-healing structures (“smart materials”)

Definition of Structural Health Monitoring

- **Structural Health Monitoring** is the process of implementing a damage detection strategy for aerospace, civil and mechanical engineering infrastructure.
- Implementation depends of specific application attributes, for example differences in time scale on which damage evolved:
  - For long term SHM, the output of this process is periodically updated information regarding the ability of the structure to perform its intended function in light of the inevitable aging and degradation resulting from operational environments.
  - After extreme events, such as earthquakes or blast loading, SHM is used for rapid condition screening and aims to provide, in near real time, reliable information regarding the integrity of the structure.

Motivation for Structural Health Monitoring

- Economic and life-safety advantage
  - Move from time-based maintenance to condition-based maintenance
  - Combat asset readiness
  - New business models
    - Manufacturers of large capital investment hardware can charge by the amount of life used instead of a time-based lease**.**
- **Driven by these motivations, the SHM process enables users to make more informed decisions about use, operation, maintenance, retirements (i.e. lifecycle management)**

The Structural Health Monitoring Process

- The Structural Health Monitoring process includes:

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 & networking

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

3. Feature selection & extraction

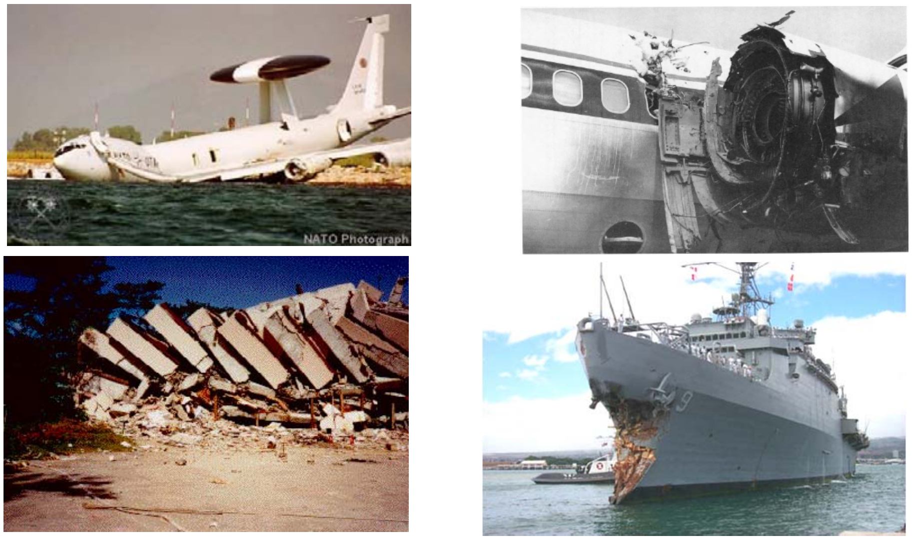
   The process of identifying damage-related information from measured data.

4. Probabilistic decision making

   Using statistical models to transform features into actual performance-level decisions

- Our goal is to first discuss each of these steps in more detail
- We will conclude the course by proposing a risk-based methodology to integrate these four steps

Illustrative Example: Are These Systems Damaged?



Did you use pattern recognition?

SHM Attempts to Answer the Following Questions

1 **Is the system damaged?**

2 **Where is the damage located?**

3 **What type of damage is present?**

4 **What is the extent of damage?**

5 **What is the remaining useful life of the structure? (Prognosis)**

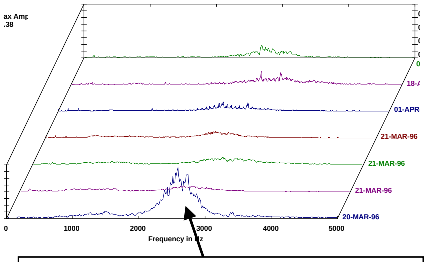
Brief History of Vibration-Based Damage Detection

- Heuristic forms of vibration-based damage detection (acoustic) have probably been around as long as man has used tools.
- Developments in vibration-based damage detection are closely coupled with the evolution, miniaturization and cost reductions in sensors, data acquisition systems 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.

Health Monitoring of Rotating Machinery

- Economic benefits have driven the development of machine condition monitoring
  - Maintenance is typically accounts for 15-40% of production costs.
- Condition monitoring provides two types of monitoring:
  - "Protective Monitoring," e.g. identify data features that are indicative of impending failure and shut machines down
    - Must establish **absolute values** on acceptable levels of feature change.
  - "Predictive Monitoring," e.g. identify tends in data features that allow for proper and cost effective maintenance planning.
    - Requires knowledge of the **feature's time rate of change**.
    - Requires correlation of change in features with other operating conditions.

Rotating Machinery Application



Before Bearing Replacement

Spectral response of machine vibrations before (bottom trace) and after bearing replacement

Engineers at semiconductor fab measure vibrations on a vacuum blower motor

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Health Monitoring of Rotating Machinery

- Data are typically acquired during normal operation or during start-up or shutdown transients and often in well-controlled environments.
- It is important to monitor non-vibration parameters to distinguish between changes in machine operating conditions and changes caused by damage. :
  - equipment and fluid temperatures, pressures, flow rates, oil debris, power consumption
- Typically, there are a tractable number of well-defines damage scenarios and locations to be monitored (example: bearing failure).
- Single-channel FFT analyzer and Piezoelectric accelerometer is commonly employed for data acquisition and recording.
- U.S. Navy’s Integrated Condition Assessment System (ICAS) is one of the most comprehensive machine condition management systems.

Early Work on Offshore Structures

- Offshore Industry spent millions of dollars during the 70’s and 80’s in an effort to launch practical damage detection and health monitoring of offshore platforms
- Numerous examples in the literature of numerical modeling efforts as well as scale-model and full-scale experiments
- Many practical problems were encountered:
  - Machine noise
  - Non-uniform inputs
  - Hostile environment for instrumentation
  - Marine growth
  - Changes in foundation with time

- Primarily studied inverse modeling approaches using resonant frequencies as the damage-sensitive feature
- Industry abandoned these study in mid 80’s

Highway Bridge Monitoring

- Study SHM techniques to augment federally mandated visual inspections.
- Driven by several catastrophic bridge failures over last 30 years
- Commercial systems for bridge health monitoring are currently available (see Nigbor, 1997)
- Asian governments are mandating the companies that construct civil engineering infrastructure periodically certify the structural health of that infrastructure.
- U.S. Federal Highway Administration has developed a center to validate bridge NDE methods.(www.fhwa.dot.gov/research/tfhrc/labs/nde/)
- Monitoring systems for bridge cables is a current area of active research

- Tsing Ma Bridge in Hong Kong (approx. $20 million for 1000+ channels of data acquisition)

Aerospace Applications

- NDE validation center established as a result of Aloha Airlines failure.
- Heath and Usage Monitoring Systems (HUMS) for rotor craft transmission and engine applications endorsed by FAA
- Modal inspection procedure developed to expedite turn around of space shuttle (it does not require removal of thermal protection system tiles).
- Several data sets from truss-like test articles has driven the development of FE model updating approaches to detect, locate and quantify damage.
- Weight minimization and extreme environments are big hurdles for sensing systems.

- Advanced instrumentation (e.g. fiber optics,) has been the focus of many studies
- Wave propagation-based damage detection and acoustic emissions are being studied extensively for this application.

Concluding Remarks

- Currently, lots of research efforts underway to develop structural health monitoring technology.
- Structural Health Monitoring is being used in practice.
- Companies offer commercial hardware/software systems for SHM
  - **Civil Structures**: VCE Vienna, Austria (www.vce.at), Roctest, Manno, Switzerland (www.roctest-group.com)
  - **Mechanical Equipment**: CSI Technologies, (www2.emersonprocess.com/en-US/brands/csitechnologies/Pages/CSITechnologies.aspx); GE-Bently Nevada (www.ge-mcs.com/en/bently-nevada.html)
  - **Aerospace Structures**: Acellent Technologies, Inc, Sunnyvale, CA (www.acellent.com), Metis Design Corp. Boston, MA (www.mdeisdesing.com)
- **Course Theme**: Structural Health Monitoring is a problem in **statistical pattern recognition**.

The Structural Health Monitoring Process

1. Operational evaluation
2. Data acquisition & networking
3. Feature selection & extraction
4. Probabilistic decision making

- **Data Cleansing**
- **Data Normalization**
- **Data Fusion**
- **Information Condensation**

Operational Evaluation

- Operational evaluation begins to answer questions regarding implementation issues for a structural health monitoring system.
  - Provide economic and/or life-safety justifications for performing the monitoring.
  - Define system-specific damage including types of damage and expected locations.
  - Define the operational and environmental conditions under which the system functions.
  - Define regulatory and business constraints.
  - Define the limitations on data acquisition in the operational environment.
- Operational evaluation will require input from many different sources (designers, operators, maintenance people, financial analysts, regulatory officials)

Justification for Implementing a SHM System

- Economic/life-safety considerations (i.e. risk profile) directly drives the implementation of the SHM system.
- At a minimum, you must be able to answer the following questions:
  - What are limitations of currently employed technology?
  - What are advantages and limitations of proposed SHM system?
  - How much will it cost to develop?
  - How much will it cost to maintain?
  - What are the costs associated with the decisions based on the SHM system performance?

Economic and/or Life-Safety Justifications for SHM

- Outside of a research environment, funds will not be devoted to SHM unless there is a economic or life-safety motive.
  - Commercial airframe and jet engine manufactures will soon lease their products and assume maintenance responsibilities. Reducing maintenance cost increases profits!
  - Oil companies invest over a billion dollars for deep water offshore platforms
  - Cost of down time is exorbitant for high capital expenditure manufacturing.
  - Loss of transportation infrastructure has significant impact on entire economy
  - Life safety is also an issue for most of these examples

Defining System-Specific Damage

- In general, the more specific one can be with regard to defining the damage to be detected, the better the chances that the damage can be detected at an early stage.
- If possible, one should specifically define:
  - Type of damage to be detected (e.g. crack, excessive deformation, corrosion)
  - Anticipated damage locations (or any other prior knowledge)
  - Critical level of damage that must be detected (e.g. crack completely through the member that is 15 mm in length, may be defined by a regulatory agency)
  - Time scale for damage evolution (e.g. damage can not grow to a critical level before the next inspection that is scheduled six months from now)

Operational and Environmental Constraints

- Operational conditions will influence loading that produces the monitored dynamic responses.
  - Traffic loading on bridges
  - Machinery and fluid storage on offshore platforms
  - Speed of rotating machinery
  - Flight maneuvers (altitude, speed) and fuel level for aircraft
- Environmental conditions can produce changes in dynamic response that must be distinguished from changes cause by damage.
  - Temperature changes on bridges
  - Sea states for offshore platforms
  - Air turbulence for aerospace structures

Data Acquisition Constraints

- Cost and accessibility are common limiting factors
- For aerospace structures weight restrictions pose significant limitations
- Spark initiation is a limitation when monitoring structures containing flammable material
- RF interference poses challenges for wireless telemetry
- Many portions of a structure will not be easily accessible for instrumentation (bridge deck, below-water-line portions of oil platforms)
- Hostile Environments (e.g. radiation, temperature, moisture)

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 the 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
    - 4 yr life compared to 20 year life of rotor
- Environmental and operation constraints on the SHM System: rotating device, wind, rain, lightning, temperature electromagnetic fields, offshore

Challenges for Operational Evaluation

- **Many high-capital–expenditure engineering systems are "one-of-a-kind" systems.**
  - Dictated by physical environment where they are built
  - More difficult to incorporate lessons learned from other nominally "similar" systems to define anticipated damage
- **Structural designs are driven by low-probability, but high consequence events**
  - Earthquake, Hurricanes
  - Terrorist actions
  - Loss-of-coolant accidents
- **However, structural systems also degrade slowly under normal use**
  - Corrosion and fatigue cracking, Freeze-thaw/thermal damage, Loss of pre-stressing forces, Vibration-induced connectivity degradation, Hydrogen enbrittlement and nuclear irradiation (NPP)
- **There is no widely accepted procedure to demonstrate rate of return on investment in an SHM/DP system**

Summary of Operational Evaluation

- Need to define the justification, goals for, and the limitations of the SHM system in as quantifiable manner as possible.
- Operational evaluation should integrate as much ***a priori* information** as possible to inform the SHM system design process.
- Such information can come from a wide variety of sources.
- Quantified operational evaluation will impact the development and of all other portions of the SHM process and, in turn, the final system performance.
- Good reference related to UAVs: J. H. MacConnell, "ISHM & Design: A review of the benefits of the ideal ISHM system," 2007 IEEE Aerospace Conf.

Organizations Associated with Machinery Condition Monitoring

- Society for Machinery Failure Prevention Technology (www.mfpt.org)
- Condition Monitoring and Diagnostic Engineering Management (www.comadem.com)
- Machinery Information Management Open Systems Alliance (www.mimosa.org)
- The Vibration Institute (http://www.vibinst.org)
- American Society for NondestructiveTesting (www.asnt.org)
- American Bureau of Shipping (www.eagle.org)

Standards for Rotating Machinery Monitoring

- American Bureau of Shipping ABS-74 Hull Condition Monitoring
- American Petroleum Institute Standard 670 (machinery protection systems)
- American Society of Nondestructive Testing ASNT-217 Corrosion: machine system condition monitoring
- ANSI S2.17-1980 (R 1986) (American national standard-techniques for machinery vibration measurements)
- ISO 3945 (in-place evaluation of larger machinery)
- ISO 7919 (mechanical vibration of non-reciprocating machines – measurement on rotating shafts and evaluation criteria)
- ISO 10368 (freight thermal containers – remote condition monitoring)
- ISO 12482 (cranes – condition monitoring)
- ISO 13372 (condition monitoring and diagnostics of machines – vocabulary)
- ISO 13373 (condition monitoring and diagnostics of machines – vibration condition monitoring general procedures)
- ISO 13374 (condition monitoring and diagnostics of machines – data processing, communication and presentation)
- ISO 13379 (condition monitoring and diagnostics of machines – general guidelines for data interpretation and diagnostic techniques)
- ISO 13380 (condition monitoring and diagnostics of machines – general guidelines on using performance parameters)
- ISO 13381 (condition monitoring and diagnostics of machines – prognostics)
- ISO 14830 (condition monitoring and diagnostics of machines – tribology-based monitoring and diagnostics)
- ISO 17359 (condition monitoring and diagnostics of machines – general guidelines)
- ISO 18436 (condition monitoring and diagnostics of machines – requirements for training and certification of personnel)
- Hydraulic Institute M122 centrifugal/vertical condition monitoring

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