FROM THE SPUTNIK ERA TO THE PRESENT:
ADVENTURES IN ENGINEERING SCIENCE OF ONE A & A Alumnus

Jan D. Achenbach
McCormick School of Engineering and Applied Science
Northwestern University

Stanford University
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ULTRASOUND

Frequency > 20,000 $Hz$ (cycles/second)

Radiated Field of an Ultrasonic Transducer

Typical example: $f = 5 \ MHz$

wavelength $\lambda = \frac{c}{f} \approx \frac{3000 \times 10^6 \ \mu / s}{5 \times 10^6 \ 1 / s}$

$\approx 600 \ \mu$

Other way to generate ultrasound:

laser irradiation (non-contact)
QNDE and SHM

NDE: Non-Destructive Evaluation
Q: Quantitative
SHM: Structural Health Monitoring Diagnostics and Prognostics
Safety Critical Structures
Schedule Based Inspection (In a Maintenance Facility)
SHM: Permanently Installed Sensors
On-Demand Assessment (On-Line)
Probabilistic Considerations
SHM: Global and Local
Classical Physics

QNDE and SHM

QNDE-Quantitative Non-Destructive Evaluation
SHM-Structural Health Monitoring

Electronics
Laser optics
Information technology
Materials engineering
Solid mechanics
Applied mathematics
Some Historical Notes

- Dark Ages of NDI
- Enlightenment
- Industrial Revolution
- Modern Times of NDE
- Upheavals
- The New Age with a Q
ENLIGHTENMENT

SECOND HALF OF THE 19TH CENTURY: DISCOVERIES AND DEVELOPMENTS IN CLASSICAL PHYSICS

• J.P. Joule: magnetostrictive effect
• J. and P. Curie: piezoelectric effect
• J.C. Maxwell: Electromagnetic Theory
• J.W.S. Rayleigh and H. von Helmholtz: Theory of Sound
• W.C. Röntgen: x-rays
Industrial Revolution
First Applications of NDI or NDT

• 1895 Wilhelm Conrad Röntgen discovers what are now known as X-rays. In his first paper, he discusses the possibility of flaw detection.
• 1880-1920 A method of crack detection is used in the railroad industry to find cracks in heavy steel parts. (A part is soaked in thinned oil, and then painted with a white coating that dries to a powder. Oil seeping out from cracks turns the white powder brown, allowing the cracks to be detected.) This was the precursor to modern liquid penetrant tests.
• 1920 H.H. Lester begins development of industrial radiography for metal parts. 1924-Lester uses radiography to examine castings to be installed in a Boston Edison Company steam pressure power plant.
• 1926 The first electromagnetic eddy current instrument is available to measure material thicknesses.
• 1927-1928 Magnetic induction system to detect flaws in railroad track developed by E. Sperry and H.C. Drake.
• 1929 Magnetic particle methods and equipment pioneered (A.V. DeForest and F.B. Doane.)
• 1930s R.F. Mehl demonstrates radiographic imaging using gamma radiation from Radium, which can examine thicker components than the low-energy X-ray machines available at the time.
• 1935-1940 Liquid penetrant tests developed (Betz, Doane, and DeForest)
• 1935-1940s Eddy current instruments developed (H.C. Knerr, C. Farrow, T. Zuschlag, and Fr. F. Foerster.)
• 1940-1944 Ultrasonic test method developed by Firestone (USA), Trost (Germany) and Sproule (UK).
• 1950 J. Kaiser introduces acoustic emission as an NDT method.
• The American Society for Nondestructive Testing was founded in 1941 as the American Radium and X-Ray Society.
UPHEAVALS

SPECTACULAR STRUCTURAL FAILURES

- Liberty Ships
- Aloha Incident
- The Crash of Flight 232
- I-35W bridge in Minneapolis
- Other Bridges
In January 1943 the one-day old T2 Tanker SS Schenectady had just completed successful sea trials and returned to harbour in calm cool weather when . . . "Without warning and with a report which was heard for at least a mile, the deck and sides of the vessel fractured just aft of the bridge superstructure."

Fracture Mechanics becomes a formal engineering discipline.
Figure 5.7A

Figure 5.7B

Figure 5.7A and 5.7B Lap Joint And Crack Formation
Figure 6. The Aloha case.
The engine explosion that led to the United Air Lines DC-10 crash last month in Sioux City, Iowa, and other recent engine problems have provoked discussion of ways to prevent serious engine failures and limit the damage they can cause to the rest of an aircraft. Federal safety officials have recommended a design review and more intensive inspections of the type of engine that broke apart over Iowa, the General Electric CF6-6, which is similar to other large turbofan engines used on jumbo jets.
Bridge Connectors
Gusset plates connect steel beams in riveted, bolted and, occasionally, in fully welded bridges. They are weight bearing but do not carry the main load. Plates are common in steel spans in the Washington area.

- Top chord truss member
- Gusset plate
- Truss members
THE NEW AGE WITH A Q
QNDE
SCHEDULE-BASED
LOCAL INSPECTION OF STRUCTURAL DEGRADATION
(Damage Parameter)

DIAGNOSTICS
• Sensor Development
• New Techniques
• Measurement Models
• Probability of Detection
• Data Processing
• Defect Characterization

PROGNOSTICS
• Damage Evolution Laws
• Probabilistic Failure Analysis
• Damage Progression Estimates
• Inspection Scheduling
FATIGUE OF METAL STRUCTURES

Stage I: pre-crack fatigue damage
Stage II: macrocrack formation
Stage III: macrocrack growth (evolution law)

What can you detect and quantify in Stages I-III

Stage IV: optimization of inspection schedule

Probabilistic Considerations
Pre-Crack Fatigue Damage

**Objective:** Develop a local NDE technique to *probe fatigue damage* and use the information to estimate *the probability of macrocrack initiation* of structures.

Theory: Fatigue Damage and Acoustic Nonlinearity

FATIGUE DAMAGE

- dislocation monopoles, dipoles
- persistent slip bands, microcrack nucleation
- macrocrack propagation

HARMONIC GENERATION

\[ f_0 \quad \frac{\omega}{c} \quad 2f_0 \quad \ldots \]

Acoustic nonlinearity parameter (\( \beta \))

- Measure \( |A_1| \) at increasing number of cycles
- Measure \( |A_2| \)

\[ \beta = \frac{8c^2 |A_2|}{\omega^2 x |A_1|^2} \]

\( c: \) wave velocity
\( x: \) distance of travel

\( \beta \) is a MEASURE OF FATIGUE DAMAGE PRIOR TO MACROCRACKING
Acoustic Nonlinearity Measurements


### 0.25 % (mass) Carbon steel

Size of macrocrack at nucleation ~ 0.25 mm (250 microns)
Modeling of Damage in Metals

Damage Model:

\[
\frac{dD}{dN} = \frac{1}{N_c} \left( 1 - \frac{r_c(\bar{\sigma})}{\Delta\sigma / 2} \right)^m \frac{1}{(1 - D)^n}
\]

\(\Delta\sigma\) - Stress range in a cycle

\(r_c(\bar{\sigma})\) - endurance limit at \(\bar{\sigma}\)

\(N_c\) - Normalizing constant

Solving for \(D(N)\)

\[
D(N) = 1 - \left( (1 - D_0)^{n+1} - \frac{(N - N_0)}{N_c} \left( 1 - \frac{r_c(\bar{\sigma})}{\Delta\sigma / 2} \right)^m \right) \frac{1}{n+1}
\]

\(D_0\) - damage at \(N = N_0\) cycles

We choose an equivalent damage parameter, to be measured by structural health monitoring
SIMPLE EXAMPLE OF PROBABILISTIC APPROACH TO DAMAGE EVOLUTION

\[ \sigma_x = \sigma \sin(\omega t) \]

\[ K = 1.12\sigma\sqrt{\pi a} \]

\[ \frac{da}{dN} = A(\Delta K)^m \]

\[ a_{N}^{1-m/2} = a_{0}^{1-m/2} + NA \left[ 1 - \frac{m}{2} \right] \left( 1.12\Delta\sigma\sqrt{\pi} \right)^m \]

\[ a_0 \rightarrow a_N \]

\[ f_0(a_0) \rightarrow f_N(a_N) \]

Probability that there exists a crack with length \( a_N > a_{cr} \) is

\[ \Pr(a_N > a_{cr} ; N) = \int_{a_{cr}}^{\infty} f_N(a_N) da_N \]
PROBABILITY OF NO DETECTION

\[ POD(a) = \frac{\alpha a^\gamma}{1 + \alpha a^\gamma} \]

\[ PND(a) = 1 - \frac{\alpha a^\gamma}{1 + \alpha a^\gamma} = \frac{1}{1 + \alpha a^\gamma} \]

Determine the probability that there exists a crack with \( a_N > a_{cr} \) which was undetected at the inspection at cycle \( N_1 \)

\[ \Pr(a_N > a_{cr}, N \geq N_1; ND) \]
$a_{cr} = 2 \text{ mm}, \text{ Single inspection at 100,000 cycles}$
Given:
• an initial crack length distribution
• an assessment time $N_L$
• **single** inspection
• a POD curve of the inspection procedure
• costs associated with failure $C_F$, replacement $C_R$ and inspection $C_I$

Aim – To find the optimum number of cycles for on-demand inspection to minimize cost function

Cost Function $C = \begin{cases} \text{Prob. of Failure at } N_1 \quad & \text{at } a > a_f \quad C_F \end{cases} + \begin{cases} \text{Prob. of Replacement at the inspection at } N_1 \quad & \text{at } a > a_{cr} \quad C_R + C_I \end{cases} \]
Cost Function $C = \left[ \begin{array}{c} \text{Prob. of } a > a_f \text{ from } 0 \text{ to } N_L \\ \text{Prob. of } a > a_f \text{ from } 0 \text{ to } N_1 \\ 0 \leq N_1 \leq N_L \\ \text{Prob. of detected } a > a_{cr} \text{ at } N_1 \\ \text{Prob. of } a > a_f \text{ of the replaced component} \\ \text{Prob. of } a > a_f \text{ for detected crack which was less than } a_{cr} \text{ at } N_1 \\ \text{Prob. of undetected } a > a_f \\ \end{array} \right] C_F + (\text{Prob. of detected } a > a_{cr} \text{ at } N_1) C_R + C_I$

- $C_F$ - Prob. of undetected $a > a_f$
- $C_R$ - Prob. of detected $a > a_{cr}$ at $N_1$
- $C_I$ - Prob. of undetected $a > a_f$

$C_F = \left( \begin{array}{c} \text{Prob. of } a > a_f \text{ from } 0 \text{ to } N_L \\ \text{Prob. of detected } a > a_{cr} \text{ at } N_1 \\ \text{Prob. of undetected } a > a_f \\ \end{array} \right) C_F + (\text{Prob. of detected } a > a_{cr} \text{ at } N_1) C_R + C_I$
Look for the minimum in the region defined by:

\[ 0 \leq N_1 \leq N_2 \leq N_L \]

For \[ N_L = 200000 \]

Minimum cost at \[ N_1 = 120000 \], \[ N_2 = 153000 \]
STRUCTURAL HEALTH MONITORING

Tough Additional Requirements for:

• Sensors
• Power Management
• Communication
• Data Management
• Extraction of Useful Diagnostic Data
• Probabilistic Prognostication with Evolution Laws

Combine Information of System Level (Global) Measurements with Local Measurements
Grand Plan

• permanently installed microsensors

• on demand or continuous condition monitoring in real time with known POD

• wireless transmission to central station

• instantaneous interpretation of sensor data

• detection of unacceptable material damage at critical high-stress locations

• monitoring of growth of material damage into critical size

• growth prediction by a probabilistic procedure

• adjustments for actual damage state at prescribed intervals

• probabilistic forecast of damage state for near term and of lifetime
Current state of structure

Damage growth characteristics

Structural Health Monitoring System

Probability of detection

Measured state of structure

Failure Model

Structural Model

Probabilistic prognosis of damage evolution
(damage vs time or cycles)

Failure probability within preset interval

low

high

Inspection and Repairs at maintenance facility
Why is SHM Better Than Schedule-Based NDI

NDI – schedule-based inspection/maintenance
SHM – on-demand (or continuous) inspection with permanently installed sensors/condition-based maintenance

Benefits of SHM:

• increased availability of aircraft
• quick assessment of potential/actual damage events
• reduced life-cycle total ownership costs
• reduced logistics
• increased safety
• performance of advanced materials
• smaller design margins of structures
Structural Inspection Performance Space

Boeing Technology | Phantom Works

Integrated Structures

Edward V. White
Boeing Phantom Works
edward.v.white@boeing.com

Seek to minimize MMH and lost service availability (cost)

Seek to minimize flaw size detection at very high (100%?) PoD with very low false alarm rate

Seek to maximize coverage with minimum disassembly
Current NDE had broad, but not full, coverage capability and small flaw size detection at the cost of long measurement time (MMH).

NDE R&D seeks faster more efficient inspections and expanding to full coverage of internal, hard to access structure.
Current SHM has limited coverage and flaw size detection is yet to be demonstrated at acceptable PoD, but is near real time.

SHM R&D seeks much broader coverage and demonstrated flaw size capability at acceptable PoD.
NDE R&D seeks more efficient inspections and expanding to full coverage of internal, hard to access structure.

SHM R&D seeks much broader coverage and demonstrated flaw size capability at acceptable PoD.

Combined NDE/SHM seeks synergies to accelerate progress.
Why is SHM So Slow In Making the Transition from Research to Practice?

Competition of schedule-based maintenance–facility inspection:

- safety record of aircraft
- accepted prognosis methods
- current methods well understood and trusted by practitioners and certifying authorities
- affordable for now
- large NDI/inspection infrastructure in place
Composite Solutions Applied Throughout the 787
Airbus Future Request
- Structural Health Monitoring

**Generation 0**
- Structure testing application
  (TR: 2003)
- Benefit:
  - structure analysis & testing
  (e.g. A380)

**Generation 1**
- In-service aircraft, off-line sensor systems
  (TR: 2008)
- Benefit:
  - maintenance

**Generation 2**
- In-service aircraft, on-line sensor systems
  (TR: 2013)
- Benefit:
  - weight saving component level
  - maintenance

**Generation 3**
- In-service aircraft, fully integrated sensor systems
  (TR: 2018)
- Benefit:
  - weight saving aircraft level
  - maintenance

Stepwise approach towards SHM application is essential
SHM Will Have to Justify its Existence
Cost-Benefit Analysis

- reduced maintenance
- increased safety
- affordable/maintainable
- near zero false-alarm rates
- reduced design margins

Huge Benefits if SHM can Justify Reduced Design Margins