Structural Health Monitoring Using
Statistical Pattern Recognition

Embedded Sensing: Acoustic Emission for SHM

Presented by
Gyuhae Park, Ph.D.

Outlines

- Introduction
- Acoustic Emission (AE) Signals
- Acoustic Emission Sensors
- AE Standards
- Source Localization
- Applications

What is Acoustic Emission?

- Acoustic Emission (AE):
  - Discontinuities in component release energy as the component is subjected to load or stress.
  - This energy travels in the form of high-frequency stress waves
  - These waves or vibrations can be captures by transducers and future processed as AE signal data
- In SHM, AE can provide comprehensive information on the origination of a discontinuity (flaw) in a stressed component
- AE can also provide information on the development of a flaw as the component is subjected to continuous or repetitive stress

Courtesy of Fuji Ceramics

AE Phenomena

- The sources of AE are, in general, local instabilities where transient elastic waves are released because of changes in the local stress field.
- The AE activity continues until a local equilibrium is reached.

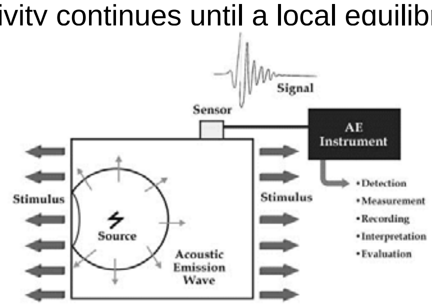


Figure courtesy of physical acoustics corporation

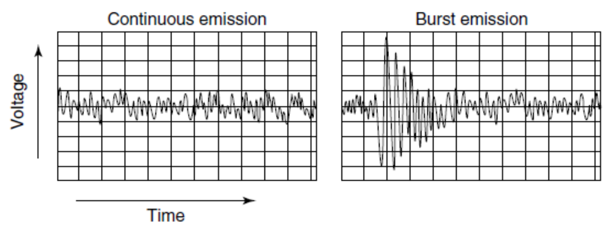
- AE sources: fatigue crack nucleation and growth, plastic deformation, creep, fracture, stress corrosion cracking, corrosion fatigue and others

AE as a SHM technique

- A passive method:
  - only detects defects when they are activated by applying a stress that is adequately large.
  - cannot interrogate a structure at will
- In general, only possible to detect and locate defects
- May cover relatively large areas (depending on applications) compared to other NDE approaches
- Not suitable for locating multiple damage sites
- Recent trend is to combine with other (active) SHM approaches
- Applications
  - Leak detection
  - Monitoring manufacturing processes (turning, welding..)
  - Corrosion monitoring
  - Impact localization and many others
- A mature technology with industrial applications from early 60s

AE Signals: continuous signals

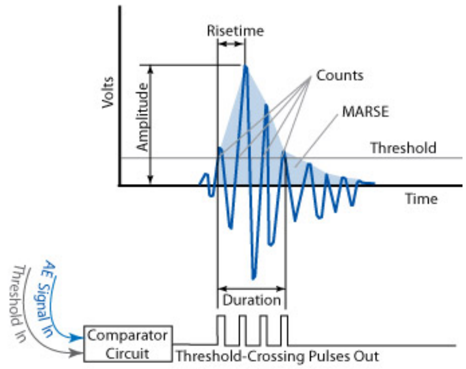
- Continuous Signals: low energy, the amplitude of the emission increases with increasing load.
  - dislocation movements in metals, leak detection
  - sufficient to use the RMS of the AE in a certain time window or spectral analysis for detection



Courtesy of Wevers and Lambrighs (2009)

AE signal – Burst signals

- Threshold: determine sensitivity
- Amplitude:
  - the highest peak value, usually in the form of dB_AE = 20 log (Vp/1 micro V)
  - determines the detectability of an AE signal
  - directly correlated to magnitude of the source
- Rise time:
  - Time interval between the first threshold crossing and the signal peak
  - Related to the propagation of the wave between the source and the sensor.

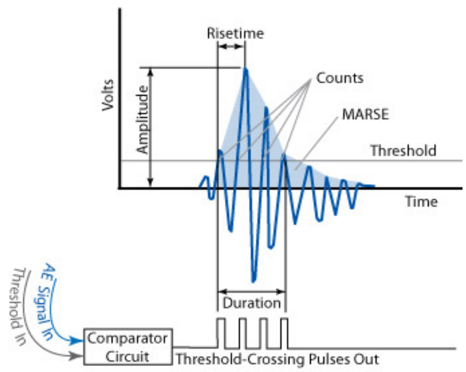


www.ndt-ed.org

- Counts:
  - number of threshold crossing
  - Widely used to describe an AE activity in earlier days
  - Provide information on signal shapes

AE signal – Burst signals

- Duration:
  - Time difference between the first and last threshold crossings
  - The relationship with Amplitude gives the information on the signal's shape
- Measured Area of Rectified Signal Envelope (MARSE):
  - sometimes referred to as energy counts
  - Most widely used measure of AE activity
  - Sensitive to amplitude as well as duration, and it is less dependent on threshold setting and operating frequency



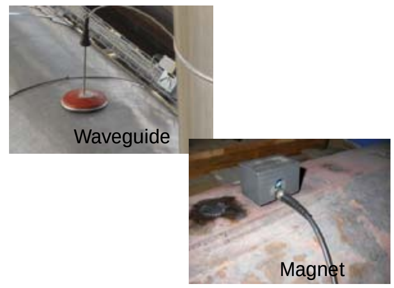
www.ndt-ed.org

AE sensors

- Piezoelectric-based sensors are widely used.
- Sensors are in the range of 20 kHz – 1 Mhz
- Unlike accelerometers, AE sensors are designed to measure the response in any direction.
- Generally categorized as a i) broadband and ii) resonance model (20 kHz: leak detection, 150 kHz: crack detection etc)
- Installation: Glue, Magnet, waveguide, etc


Physical acoustics corporation

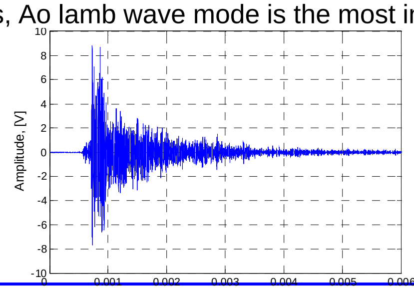

Digital wave corporation



Courtesy of Muravin

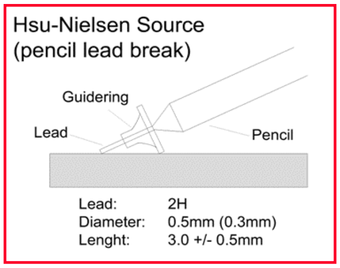
AE attenuation/wave velocity

- Acoustic emission is nothing but the stress wave propagation
- Subjected to attenuation due to
  - Geometry spreading effects
  - Scatter at boundary and discontinuity
  - Material damping
- Wave velocity
  - Typical wave velocity in solids: 1500-6000 m/s
  - Among others, Ao lamb wave mode is the most important wave in AE.



AE calibration

- A simulated AE source (Pencil-lead fracture) is typically used to determine the degree of attenuation and wave velocity for deploying sensors
- Breaking a 0.5 mm 2H pencil lead
  - Standard Guide for Determining the Reproducibility of Acoustic Emission Sensor Response (ASTM E976-84)



http://www.ndt.net/ndtaz/ndtaz.php

Courtesy of Muravin

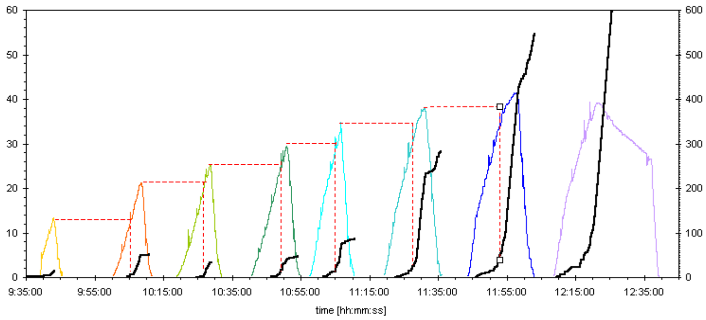
AE intersensor distance

- From Prof. John Summerscales of University of Plymouth, UK
  (*http://www.tech.plym.ac.uk/sme/mats324/PowerPoint/MATS324A12%2520NDT)*

FREQUENCY	RANGE	MATERIAL	APPLICATION
30 kHz	100 m	steel	pipelines
75 kHz	10 m	composites	tanks
175 kHz	10 m	steel	tanks
375 kHz	1 m	steel	welds
750 kHz		--- high noise situations ---	

Kaiser Effects of AE

- Absence of detectable AE at a fixed sensitivity level, until previously applied stress levels are exceeded.
  - Each AE signal may have a “now or never” quality.
  - If AE is observed prior to a previous maximum load, it indicates that some type of new damage has occurred
  - Careful attention must be paid to the loading schedule if AE testing is to be successful.



- Black line: AE activity
- Thin lines: load
- Dashed lines: Kaiser effect

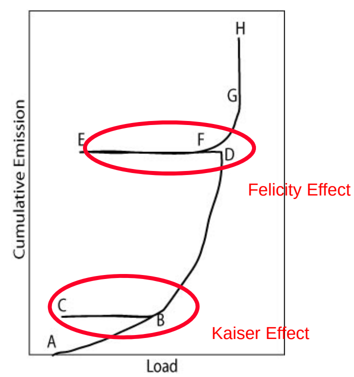
Felicity Effect

- As with accumulation of damage, Kaiser effect begins to breakdown
  - Observe AE at a lower loading
  - Prominent for composite structure (FRP and steel reinforced concrete)
  - Used to predict failure loads in structures

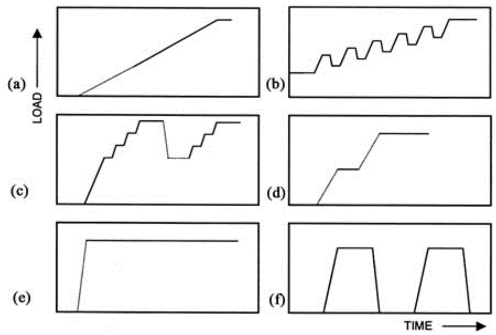
- Felicity Ratio (FR)

$$= \frac{\text{Stress at onset of AE}}{\text{Previous maximum stress}}$$

- FR less than 1 implies damage accumulation



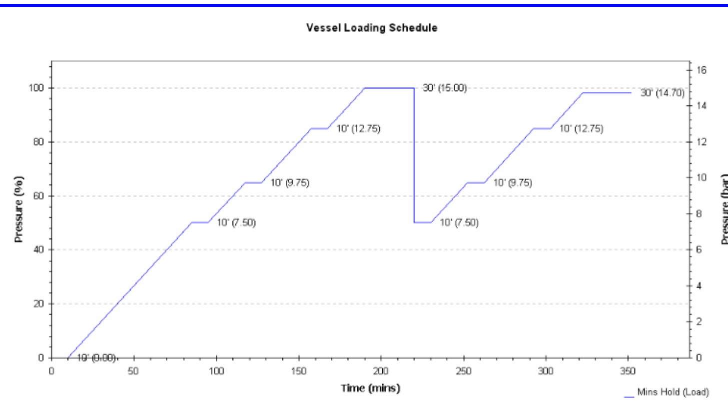
AE: controlled loads (Pollock 2004)



a) compressed gas tube;
(b) fiberglass pressure vessel;
(c) metal pressure vessel;
(d) railroad tank car,
(e) railroad tank car, mechanical loading;
(f) bucket truck.

- Developed as as AE testing procedures, evaluation criteria and international standards
- The acoustic emission inspector takes responsibility to ensure that the loading is carried out according to procedure

ASME, Pressure Vessel and Boiler Codes, Section V, Article 12 : AE Examination of Metallic Vessels During Pressure Testing



- The standard require an evaluation based on AE counts during a specified load increase, Felicity ratio, number of large amplitude hits, activity during load hold, total activity (number of AE signals, hits).
- The specific numbers for the criteria depend on the structure type, its history and other considerations and are defined in the documentation concerning the test procedure.

AE Standard

American Society for Testing and Materials (ASTM)

- E569-97 Standard Practice for Acoustic Emission Monitoring of Structures During Controlled Stimulation
- E650-97 Standard Guide for Mounting Piezoelectric Acoustic Emission Sensors
- E749-96 Standard Practice for Acoustic Emission Monitoring During Continuous Welding
- E750-98 Standard Practice for Characterizing Acoustic Emission Instrumentation
- E976-00 Standard Guide for Determining the Reproducibility of Acoustic Emission Sensor Response
- E1067-96 Standard Practice for Acoustic Emission Examination of Fiberglass Reinforced Plastic Resin (FRP) Tanks/Vessels
- E1106-86(1997) Standard Method for Primary Calibration of Acoustic Emission Sensors
- E1118-95 Standard Practice for Acoustic Emission Examination of Reinforced Thermosetting Resin Pipe (RTRP)
- E1139-97 Standard Practice for Continuous Monitoring of Acoustic Emission from Metal Pressure Boundaries
- E1211-97 Standard Practice for Leak Detection and Location Using Surface-Mounted Acoustic Emission Sensors
- E1316-00 Standard Terminology for Nondestructive Examinations
- E1419-00 Standard Test Method for Examination of Seamless, Gas-Filled, Pressure Vessels Using Acoustic Emission
- E1781-98 Standard Practice for Secondary Calibration of Acoustic Emission Sensors
- E1932-97 Standard Guide for Acoustic Emission Examination of Small Parts
- E1930-97 Standard Test Method for Examination of Liquid Filled Atmospheric and Low Pressure Metal Storage Tanks Using Acoustic Emission
- E2075-00 Standard Practice for Verifying the Consistency of AE-Sensor Response Using an Acrylic Rod
- E2076-00 Standard Test Method for Examination of Fiberglass Reinforced Plastic Fan Blades Using Acoustic Emission

American Society of Mechanical Engineers (ASME)
Pressure Vessel and Boiler Codes

- **Section V, Article 11 : AE Examination of Fiber-Reinforced Plastic Vessels**
- **Section V, Article 12 : AE Examination of Metallic Vessels During Pressure Testing**
- **Section VII, Division 1 : Use of AE Examination in Lieu of Radiography**
- **Section X, Article RT-6 : Acceptance Test Procedure for Class II Vessels**
- **Section XI, Article 11 : Continuous Surveillance for Nuclear Power Plants**
- **ASME/ANSI RTP-1 : Reinforced Thermoset Plastic Corrosion Resistance Equipment**
- **(Mandatory Appendix M - 10 AE Examination)**

AE Standard

European Working Group on Acoustic Emission (EWGAE)

- **Code I : Location of Sources of Discrete Acoustic Events (1981)**
- **Code II : Leak Detection (1984)**
- **Code III : Examination of Small Parts (1984)**
- **Code IV : Definition of Terms in AE (1985)**
- **Code V : Recommended Practice for Specification, Coupling and Verification of the**
- **Piezoelectric Transducers Used in AE (1985)**
- **Code VI : Recommended Practice for Verifying the Performance of Acoustic Emission Equipment Prior to Testing**

The Japanese Society for Non-Destructive Inspection(JSNDI)

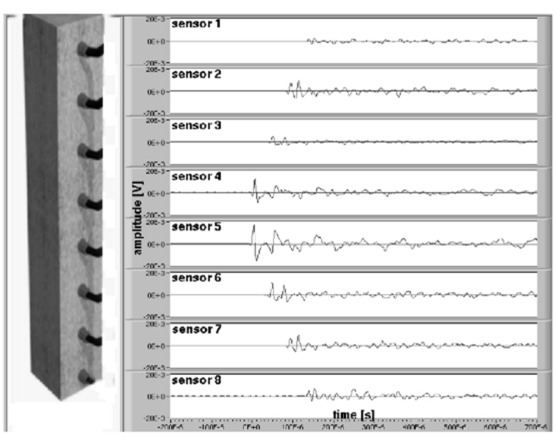
- **NDIS-2106 : Evaluation of Performance Characteristics of Acoustic Emission Testing**
- **Equipment (1979)**
- **NDIS-2049 : Acoustic Emission Testing of Pressure Vessel and Related Facilities**
- **During Pressure Testing(1979)**
- **NDIS-2412 : Acoustic Emission Testing of Spherical Pressure Vessel Made of High**
- **Tensile Strength Steel and Classification of Test Results (1980)**

Noise Rejection in AE

- Any unwanted signals could be measured by AE sensors
  - Friction by movable connectors or loose bolts
  - Impact by rain, dust, flying objects
  - Cycling noise by rotating machines
  - EMI
- Control of Noise Sources (by Maruvin)
  - Rise Time Discriminator : significant difference between rise time of mechanical noise and AE
  - Frequency Discriminator: band pass filters in DAQ.
  - Master – Slave Technique: Master sensor are mounted near the area of interest and are surrounded by slave or guard sensors. The guard sensors eliminate noise that are generated from outside the area of interest.

Source localization – Zone location/hit sequence method

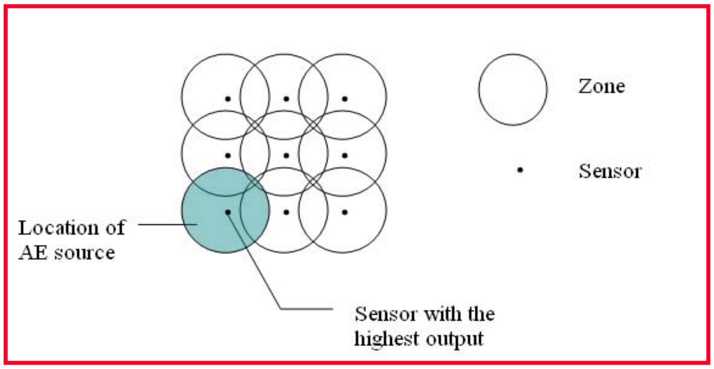
- The Sensor
  - with the highest amplitude
  - and/or the first arrival of AE is closest to the source.
- Zonal location aims to trace the waves to a specific zone or region around a sensor.
  - Could be lengths, areas or volumes depending on the dimensions of the array.
- Leak detection: by signal strength comparison at Several sensors



Courtesy of Grosse and Ohtsu (2008)

Source Localization – Zone location method

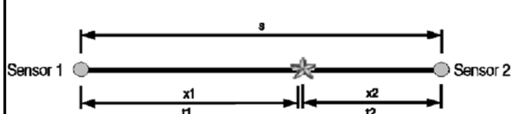
- May not provide the exact location
- Require low computational efforts



Courtesy of Muravin

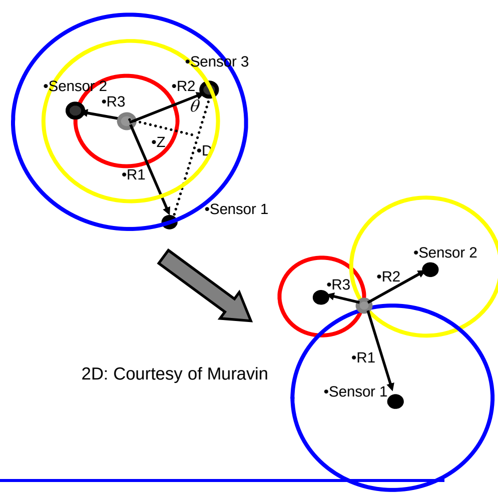
Source Localization – Point location method

- Based on the difference in time of arrival for know velocity
- Linearity assumption: Pipelines, plates



$$x_2 = \frac{1}{2}(s - (t_1 - t_2)V)$$

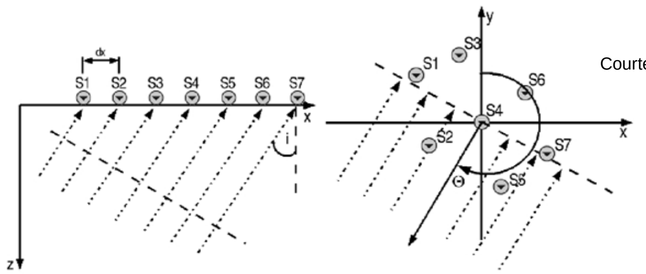
1D



2D: Courtesy of Muravin

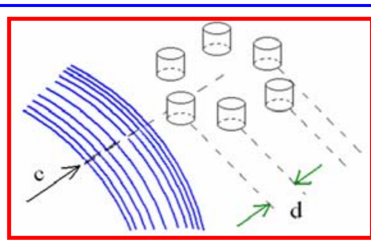
Other Localization Algorithms

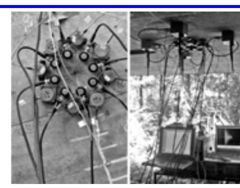
- Grid Search: The test specimen is discretized into a particular grid, and the travel times from any point in the grid to each sensors are calculated.
- Machine learning approaches: Neural Network, pattern recognition
- Beamforming algorithms: improve the SNR

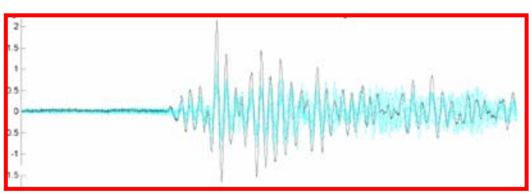


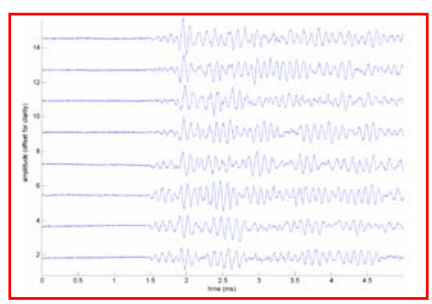
Courtesy of Grosse and Ohtsu (2008)

Beamforming of AE (by McLaskey et al. 2008)





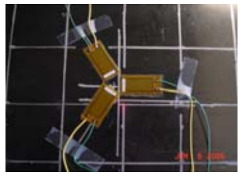


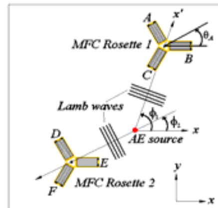


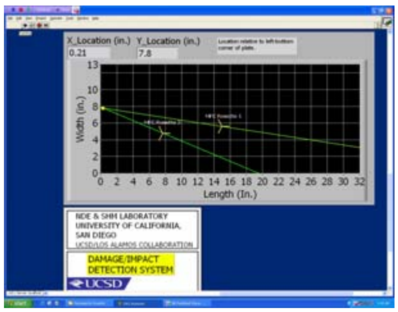
- Cost effective, suited for wireless networks, reliable

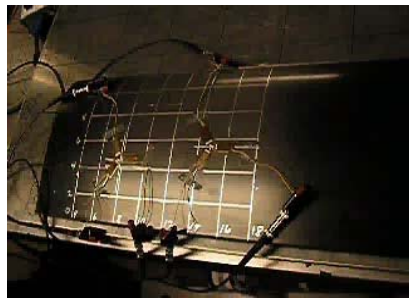
Acoustic Emission for Impact Identification (Matt et al 2006)

- MFC rosette concept

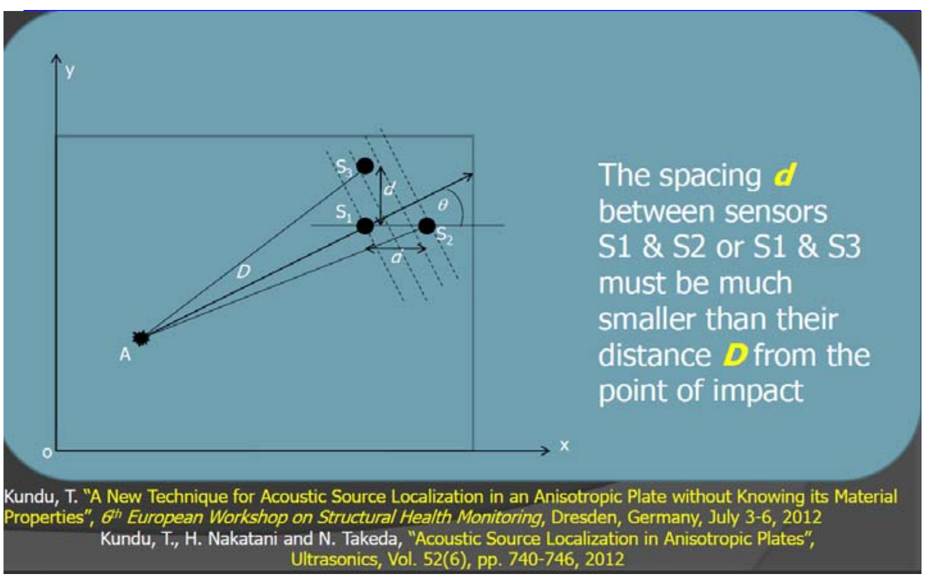






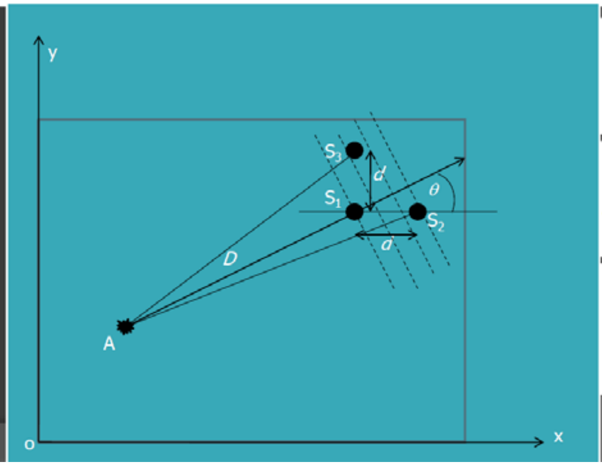


Acoustic Emission for Impact Identification (Kundu, 2012)



Acoustic Emission for Impact Identification (Kundu, 2012)

$$\theta = \tan^{-1}\left(\frac{y_1 - y_A}{x_1 - x_A}\right) \approx \tan^{-1}\left(\frac{y_2 - y_A}{x_2 - x_A}\right) \approx \tan^{-1}\left(\frac{y_3 - y_A}{x_3 - x_A}\right)$$

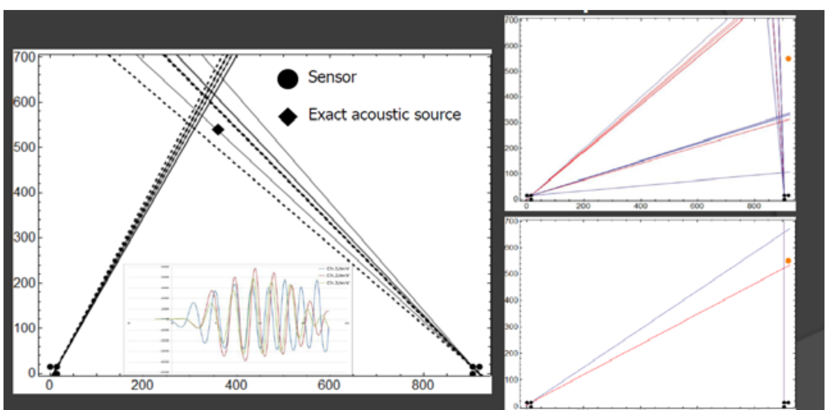


$$\Delta t_{12} = \frac{d\cos\theta}{c(\theta)}$$

$$\Delta t_{13} = \frac{d\sin\theta}{c(\theta)}$$

$$\theta = \tan^{-1}\left(\frac{\Delta t_{13}}{\Delta t_{12}}\right)$$

Acoustic Emission for Impact Identification

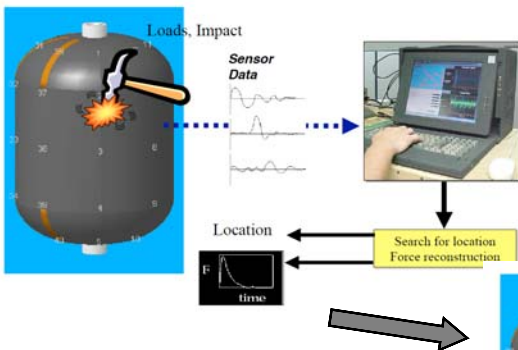


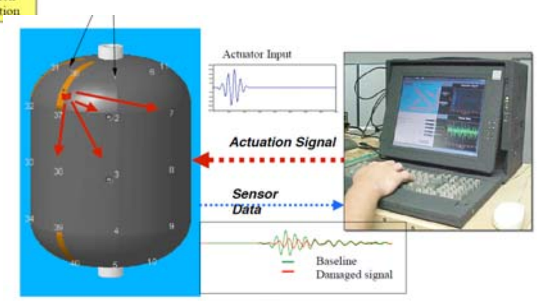
Kundu, T., H. Nakatani and N. Takeda, "Acoustic Source Localization in Anisotropic Plates", Ultrasonics, Vol. 52(6), pp. 740-746, 2012

Nakatani, H., , T. Kundu, K. Ito and N. Takeda, " Difficulties Associated with the Acoustic Source Localization in Anisotropic Plates and its Solution", IWSHM, Stanford University, Sept. 10-12, 2013

Could detect impact points without knowing the velocity profile or plate properties

Impact identification to trigger active-sensing (Chang, 2003)

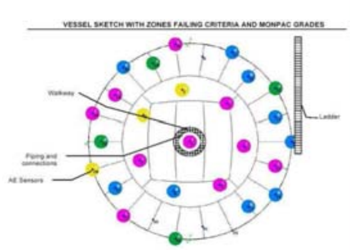




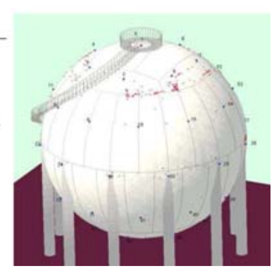
- Triggers the active-sensing to estimate the effects of impacts

AE applications: Pressure Vessels/tanks

- Challenges for NDE/SHM
  - Diameter range from 10 to 25m
  - Welded length over 400 m
  - Inaccessible, insulation
- The most successful application of AE
- MONPAC: AE based expert system for evaluating the structural integrity of metallic pressure vessels, spheres, columns and tanks. Consists of AE test procedures and evaluation criteria. Developed by Monsanto Chemical Company in late 70s and 80s

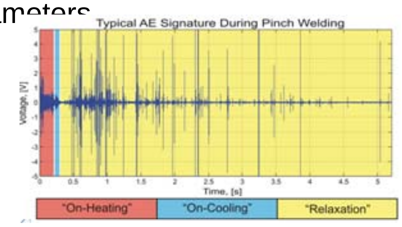


Physical acoustic corporation



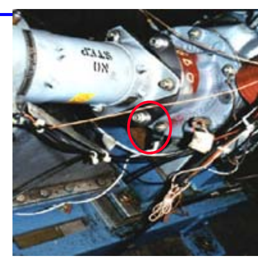
AE applications: Machining Process

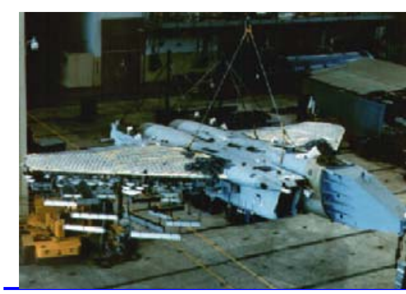
- AE has been widely used in machining process. The primary applications includes
  - Quality assurance of marching part
  - Tool condition monitoring
- Allows "in-process monitoring"
- The process applied to welding, turning, drilling, grinding, milling, precision machining, etc
- Significant involvement with machine learning algorithms
- Repeatability/reproductivity is an issue – heavily dependent on process parameters

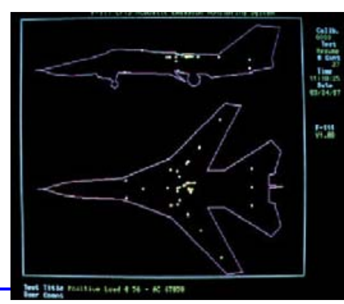


AE Applications: Aerospace structures

- AE-HUMS: detecting damage in helicopter drivetrain components.
- Aircraft full-scale fatigue test:
  - Fatigue load was applied based on actual flight data
  - Mainly focused on the lug assembly







Figures courtesy of Finlayson et al. 2001

AE Applications: Aerospace structures

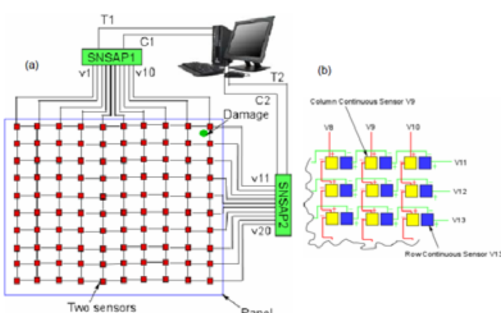
- Detect damage initiation in curved, cored, full-scale composite panels typical of aircraft components by Physical acoustics corporation and Drexel Univ. (2008)
- Panels were subjected to loading after an intentional notch was created through simulated tool drop or blade impact
- AE was employed to monitor progression of the damage notch tip as an early-warning device for anticipating imminent fracture failure.

Courtesy of Physical Acoustics Corporation

AE Applications: Other applications includes

- Rotating Machinery
- Composites
- Wind turbine blades
- Civil Structures – Concrete/bridges

Oregon DOT

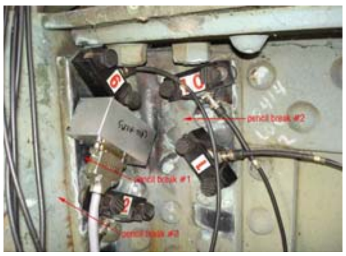


Continuous sensors by Schulz and Sundaresan (2006)

http://www.ndt-ed.org

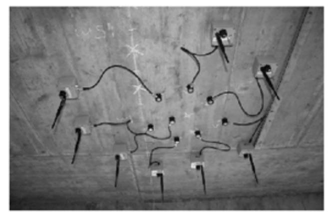
AE Applications

- Recent trends with
  - MEMS or Fiber Optics for AE sensors
  - Integration with wireless technology
  - Integration with active-sensing technique



Ozevin et. Al (2006)

http://www.tisec.com



Grosse et al (2006)

Limitations of AE testing

- Repeatability: AE activity is unique and cannot be reproduced
- Attenuation: Difficulties for structures with high damping/scattering sources
- History dependence: The loading history of a structure will be useful
- Noise: AE can be subjected to external noise
- Structures: Complex geometry may impose complexities in recorded waveforms for analysis

Useful References

- M. Wevers, K. Lambrighs, "Applications of Acoustic Emission for SHM: A Review," Encyclopedia of Structural Health Monitoring, 2009
- A. A. Anastasopoulos1, D. A. Kourousis1, P.T. Cole, 2008, "Acoustic Emission Inspection of Spherical Metallic Pressure Vessels," The 2nd International Conference on Technical Inspection and NDT (TINDT2008)- October 2008 - Tehran, Iran
- Finlayson, R.D., Friesel, M., Carlos, M., Cole, P., Lenain, J.C., "Health Monitoring of aerospace structures with acoustic emission and acousto-ultrasonics," Insight, 43: 2001
- Grosse, C.U., Glaser, S.D., Kruger, M. 2006, "Condition monitoring of concrete structures using wireless sensor networks and MEMS," Proc. SPIE, Vol. 6174, 61741C (2006); doi:10.1117/12.657303
- Li, X., (2002)," A brief review: acoustic emission method for tool wear monitoring during turning," International Journal of Machine Tools & Manufacture 42, 157–165
- MONPAC Procedure for Acoustic Emission Testing of Metal Tanks/Vessels, August 1992
- MBA, D, 2002, "Applicability of Acoustic Emissions to monitoring the mechanical integrity of bolted structures in low speed rotating machinery: case study," NDT&E International Journal, 35, 293-300
- G.C. Mclaskey, S.D. Glaser, C. Grosse (2008): Acoustic emission beamforming for
- enhanced damage detection. Proc. SPIE Vol. 6932, Smart Structures and Materials 2008:
- Ozevin, D., Greve, D.W., Oppenheim, I.J., Pessiki, S., "Resonant Capacitive MEMS Acoustic Emission Transducers," Smart Structures and Materials, Volume 15, No. 6, December 2006, pp. 1863-1871
- Pollock, A.A, 2008,"Loading and Stress in Acoustic Emission Testing," tutorial paper http://asnt.org
- M.J. Schulz, M.J. Sundaresan, Smart Sensor System for Structural Condition Monitoring of Wind Turbines, National Renewable Energy Laboratory report 2006
- www.muravin.com
- www.ndt-ed.org
- Grosse, C.U., Ohtus M. (Eds), Acoustic Emission Testing, ISBN 978-3-540-69895
- Geng, R. (2006), "Modern acoustic emission technique and its application in aviation industry," Ultrasonics 44, 1025-1029
- Miller, R., Hill, E., Acoustic Emission Testing in Nondestructive Testing Handbook, 3rd edition, 2005