IOWA STATE UNIVERSITY

Aer E 322: Aerospace Structures Laboratory

Week 11-12 Lecture:

NDE from 30,000 feet:
A Short Introduction to Nondestructive Evaluation

Last update: March 26, 2022

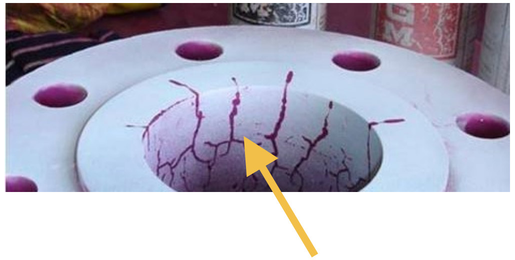
What is Nondestructive Evaluation?

- Nondestructive evaluation (NDE) or testing (NDT) is the *examination of an object with technology that does not affect the object's future usefulness* by American Society of Nondestructive Testing
- In a broader sense, NDE refers to *techniques or processes to **evaluate** the **state** of an **object** with the least amount of **destruction** or alteration of its current state*
- Here ***evaluate*** the ***state*** includes detect defects within the object, characterize object's material properties and their changes, determine object's service condition, etc.
- ***Object*** can be as large as the entire building, ship, aircraft or as small as a nano-size part
- Amount of ***destruction*** or alteration usually is very small; negligible in most cases

Why Learning Nondestructive Evaluation?

More than a line on your resume!

- For modern aero-structure, it has been increasingly important to bring in NDE at the early stage of design
- NDE assesses the key issues of in-service inspectability that is critical to the long-term safety of the structures
- This is known as ***unified life-cycle engineering***, an approach that combines aspects of concurrent engineering, total quality management, and retirement-for-cause strategies*

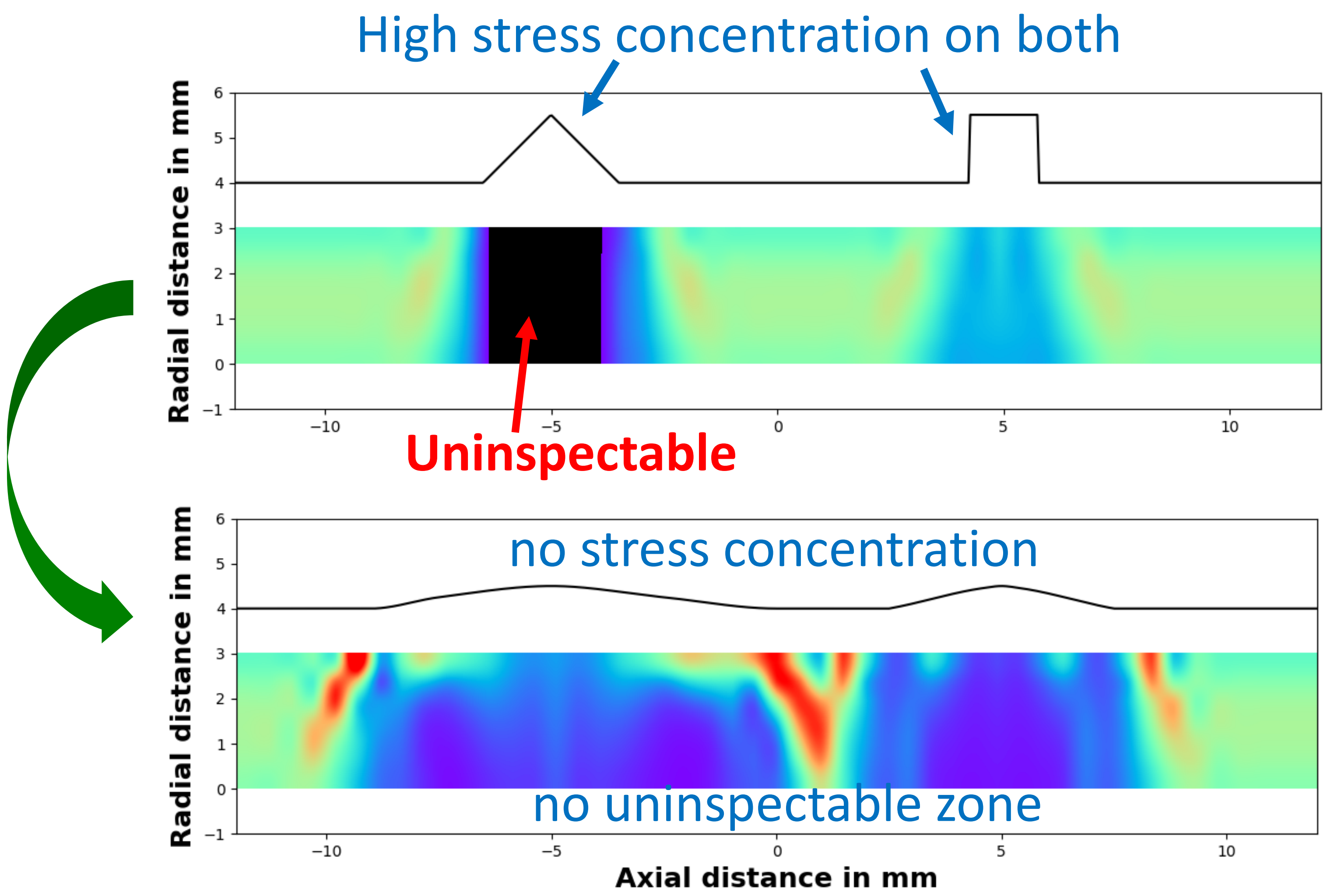


Is the inner wall accessible for inspection of e.g. cracking?

*L. W. Schmerr and D.O. Thompson, "NDE and Design - A Unified Life-cycle Engineering Approach," Review of Progress in Quantitative Nondestructive Evaluation, Vol. 12, 1993, pp. 2325-2331.

Why Learning Nondestructive Evaluation? (cont.)

Inspection coverage map: design iterated to achieve the optimal geometry of a part

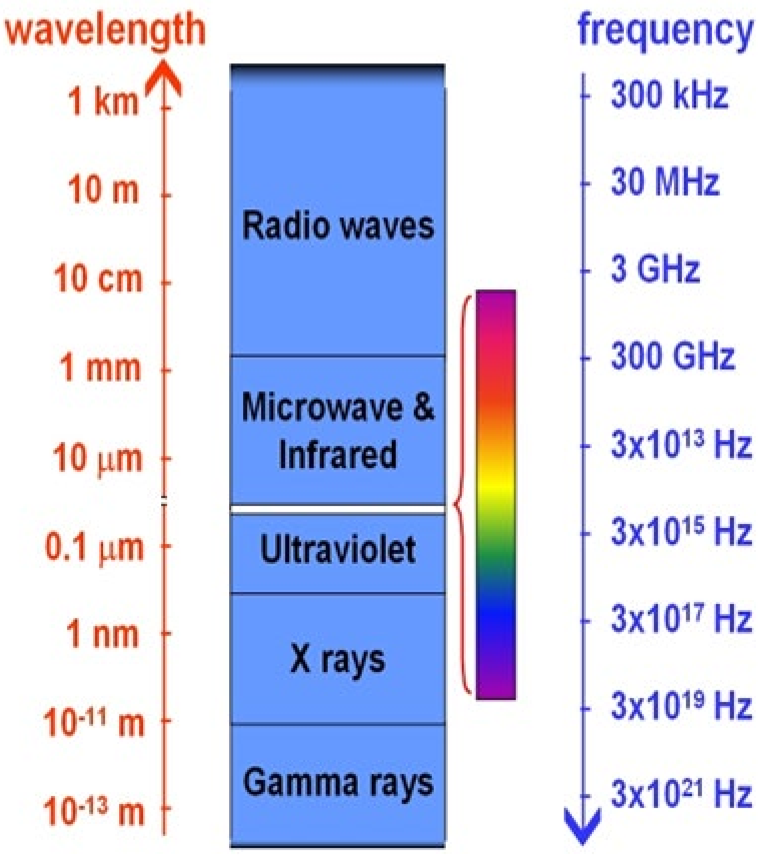


NDE Technique Overview

- The field of NDE is broad and applications can be found in a variety of engineering and science disciplines. It can be generalized to cover many other fields
- A rough list containing common NDE techniques may look like:
  - **Visual Examination**
    - Leak testing
  - **Chemical Testing**
    - liquid penetrant
  - **Mechanical Vibration**
    - Sonics: tap testing, modal testing
    - Ultrasonics: contact, immersion, guided, phase array, air-coupled, resonance, microscopy
    - Acoustic emission

NDE Technique Overview (cont'd)

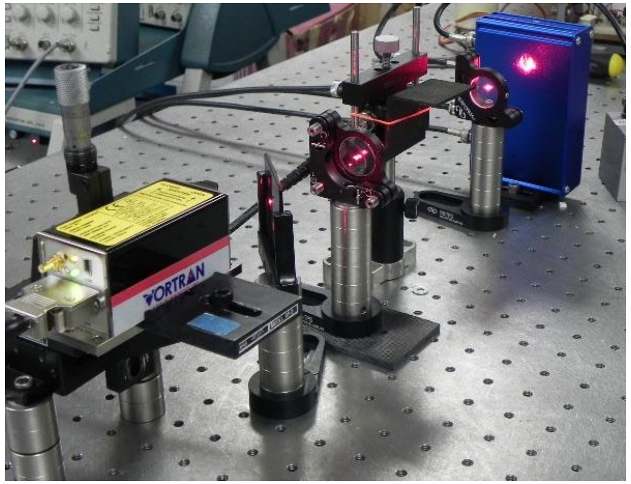
- **Electromagnetic Radiation**
  - Magnetic particle, magnetic flux leakage
  - Magnetic resonance imaging
  - Eddy current
  - Microwave, millimeter wave
  - Infrared: terahertz, thermography
  - Laser: shearography, holography
  - Optics: microcopy
  - Scanning electron microscopy
  - Fluorescent, ultraviolet



- **Radiography**
  - X-rays: computed tomography
  - Gamma rays
  - neutron

NDE Technique Overview (cont'd)

- **Combined or Hybrid Techniques**
  - Laser ultrasound
  - Electro magnetic acoustic (EMAT)
  - Sonic-IR
  - Fluorescent penetrant
- **Processing and Analysis Methods**
  - Signal and image processing
  - Modeling
  - Probability of detection
  - Failure analysis, quality control
- **Robotics, Machine Learning/Artificial Intelligence**



Objectives and Scopes of this Lab

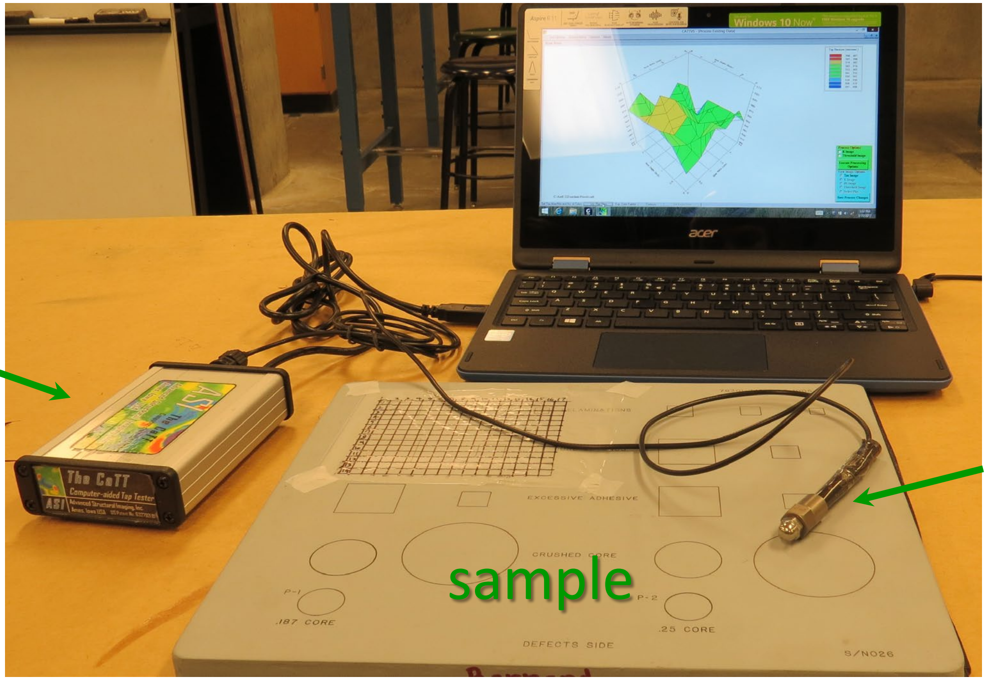
- This new NDE lab unit is designed to provide early exposure and hand-on experience of NDE to AerE undergraduate students
- We will focus on Tap testing, Ultrasonics and Eddy current as the representative techniques by their portability and accessibility at ISU
- This lecture provides only basics of each of these techniques to be exercised in the lab, and can not be a thorough coverage due to time and scope limitations

Tap Testing

- Tap test is an age-old technique. Ancestors had long learned to determine objects' inner state by tapping them from outside, e.g. *"Is that melon ready to eat?"*
- In NDE, tap testing is very easy to perform. One simply takes a solid mass such as a coin or a hammer to tap on the surface of the sample. In the audio frequency range, normal regions will produce ordinary sounds of regular pitch, while defected regions produce dull sounds of lower pitch (usually)
- Tap test method has proven very cost-effective to detect cracks, corrosion, impact damage and delamination in composite parts

Tap Testing (cont'd)

- Over the years, tap testing in NDE has evolved from a qualitative low-tech test to a quantitative computerized technique
- In this course we use a tap system called computer-aided tap tester (CATT) invented by ISU-CNDE researchers

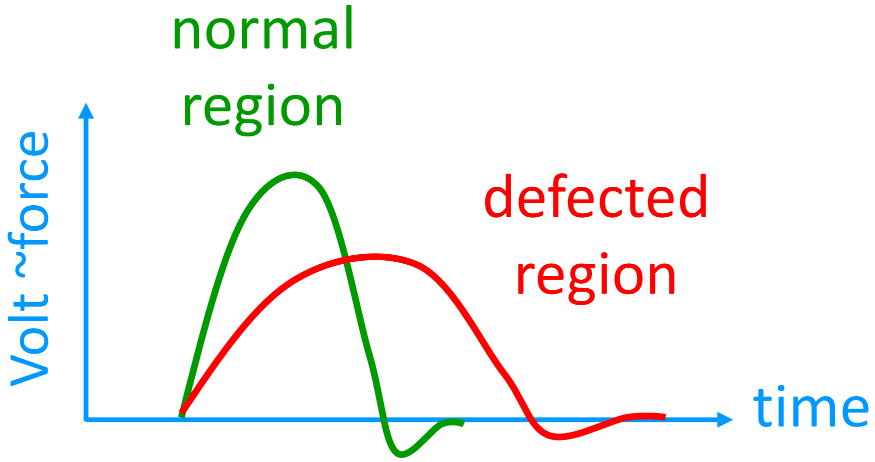


Tap Testing (cont'd)

- CATT works by determining the local stiffness variations from contact-time measurements between the tapping head and the part surface
- The contact-time duration can be related to the structure stiffness via a simple grounded spring model

$$T = \pi\sqrt{\frac{M}{K}} \Rightarrow K = \frac{\pi^2 M}{T^2}$$

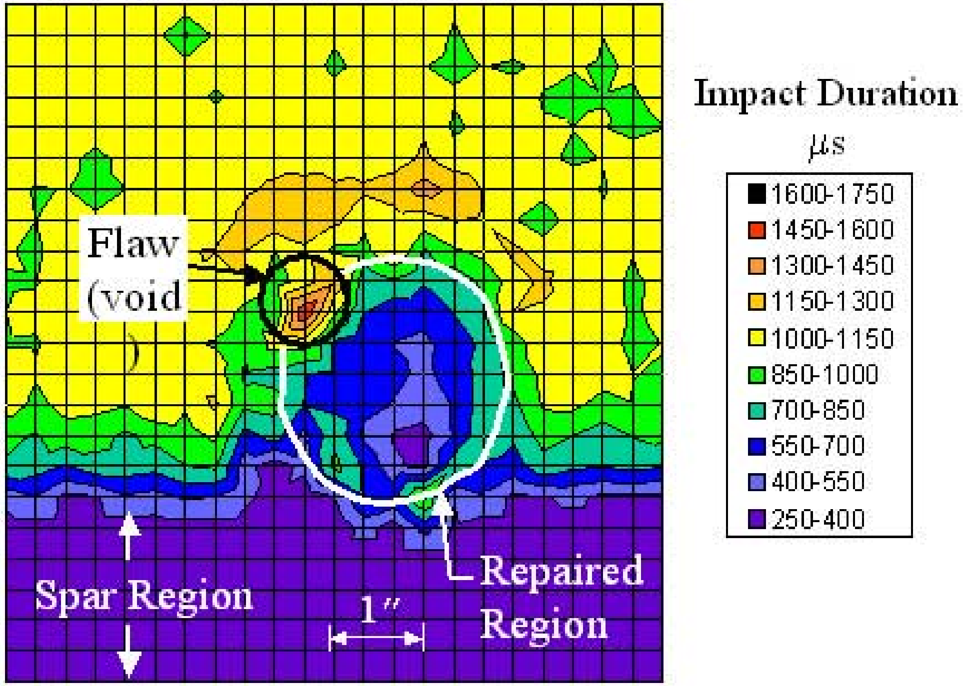
T=contact-time duration measured by CATT
M=known tapper head mass
K=part surface stiffness to be determined



- By tapping on the part surface in a grid pattern, a test image can be generated from the contact time or local stiffness measurements

Tap Testing (cont'd)

Black Hawk UH-60 rotor blade under testing at the Army Aviation support facility in Boone, Iowa

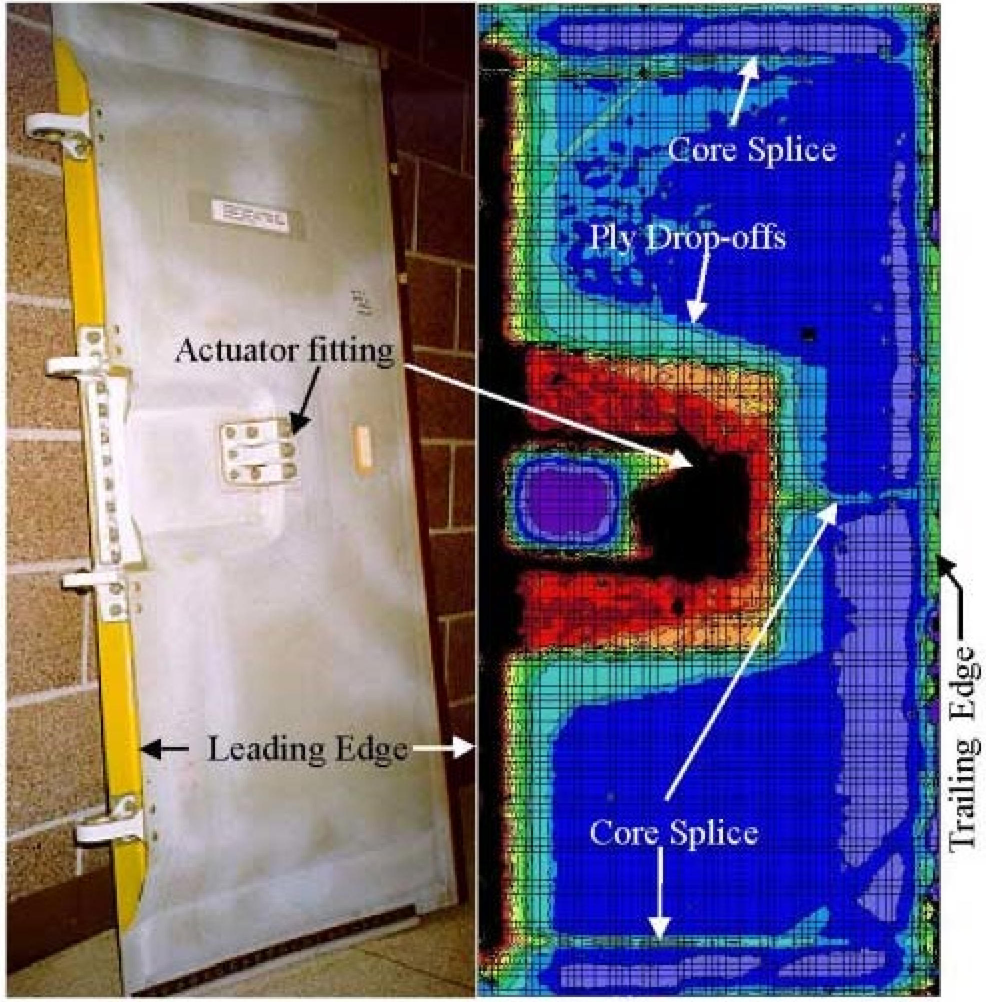


1 unit on image is 0.8 cm

Courtesy: Advanced Structural Imaging, Inc.

Tap Testing (cont'd)

Test stiffness image of B767 outboard spoiler

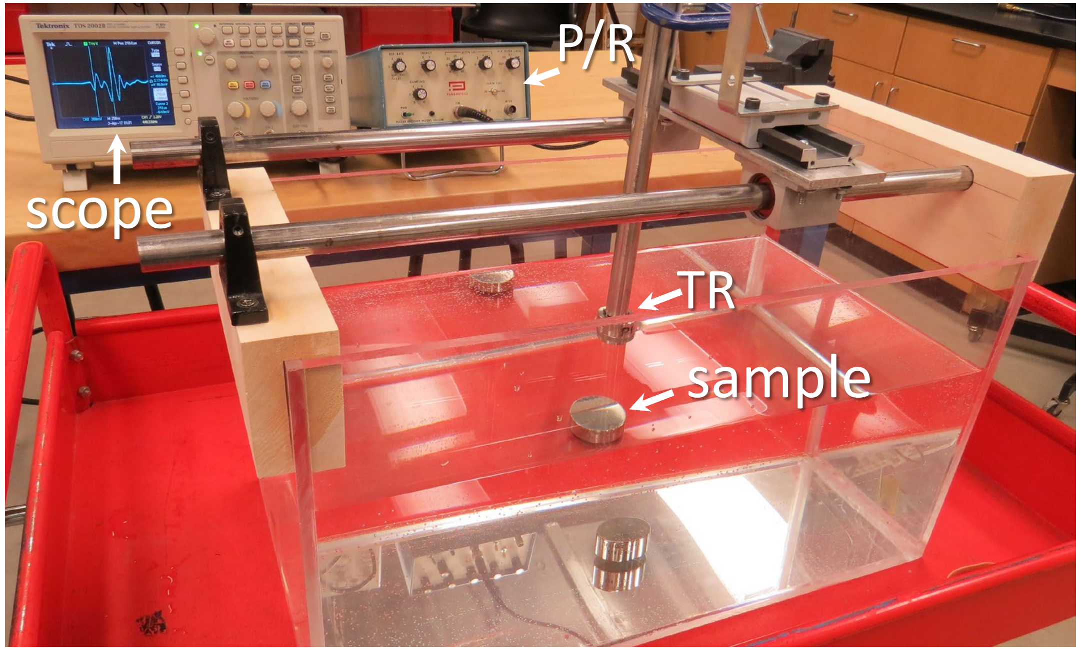


Courtesy: Advanced Structural Imaging, Inc.

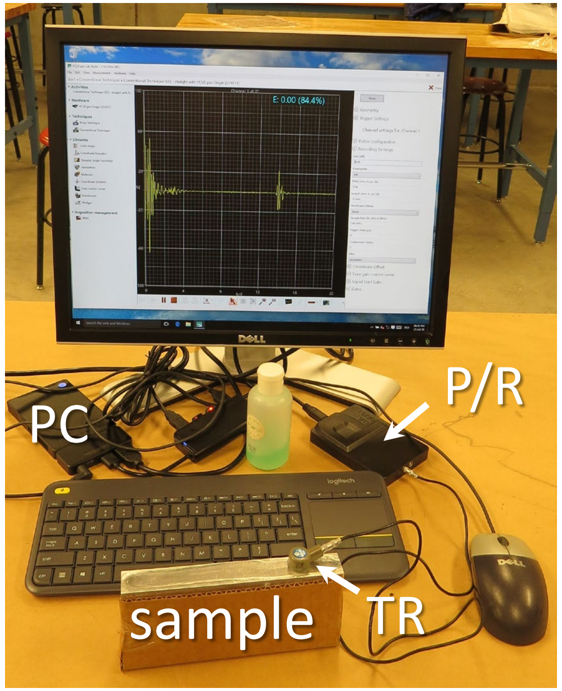
Ultrasonic Testing

- Ultrasonic testing (UT) is one of the most widely used NDE techniques applicable to a wide range of materials
- The basic equipment units consist of a transducer (TR), a pulser/receiver (P/R) and an oscilloscope or computer/screen for display, operated in either contact or immersion mode

conventional analog system
(immersion mode shown)



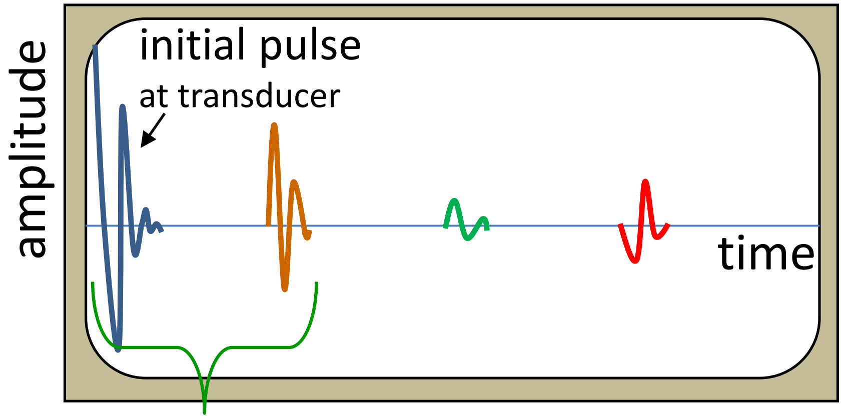
modern digital compact system
(contact mode shown)



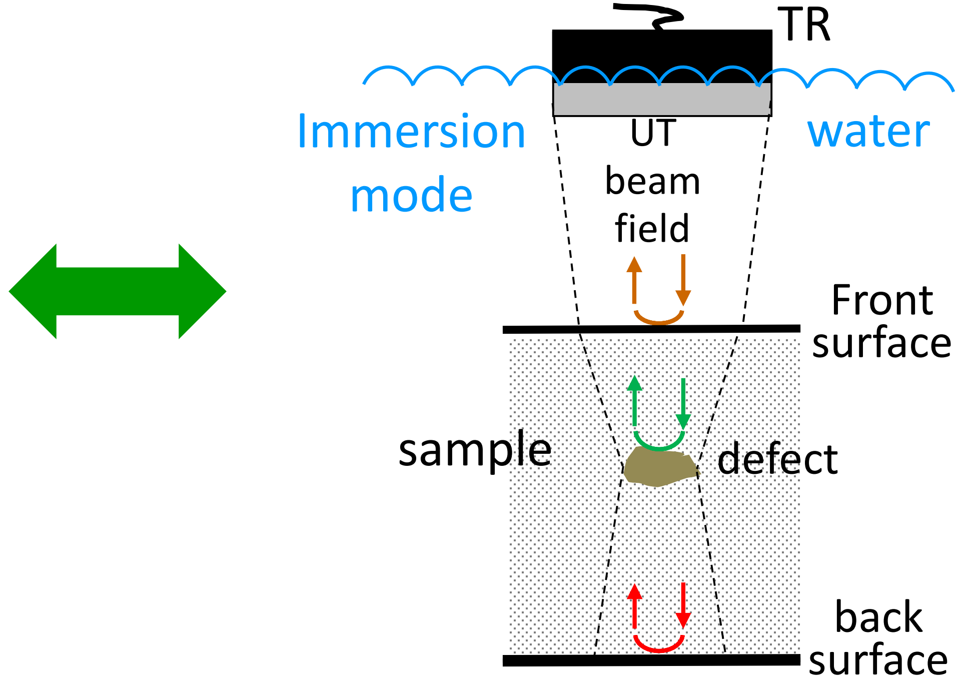
Ultrasonic Testing (cont'd)

- The pulser/receiver generates wide-band electric pulse to the transducer which converts it (via piezoelectric effect) into mechanical UT pulse to transmit into the sample
- As the incident UT pulse interacts with the sample front surface, defect and back surface, corresponding echoes reflect back. These echoes collectively are called **A-scan**. The individual echo strength is usually proportional to its reflecting surface area

A-scan

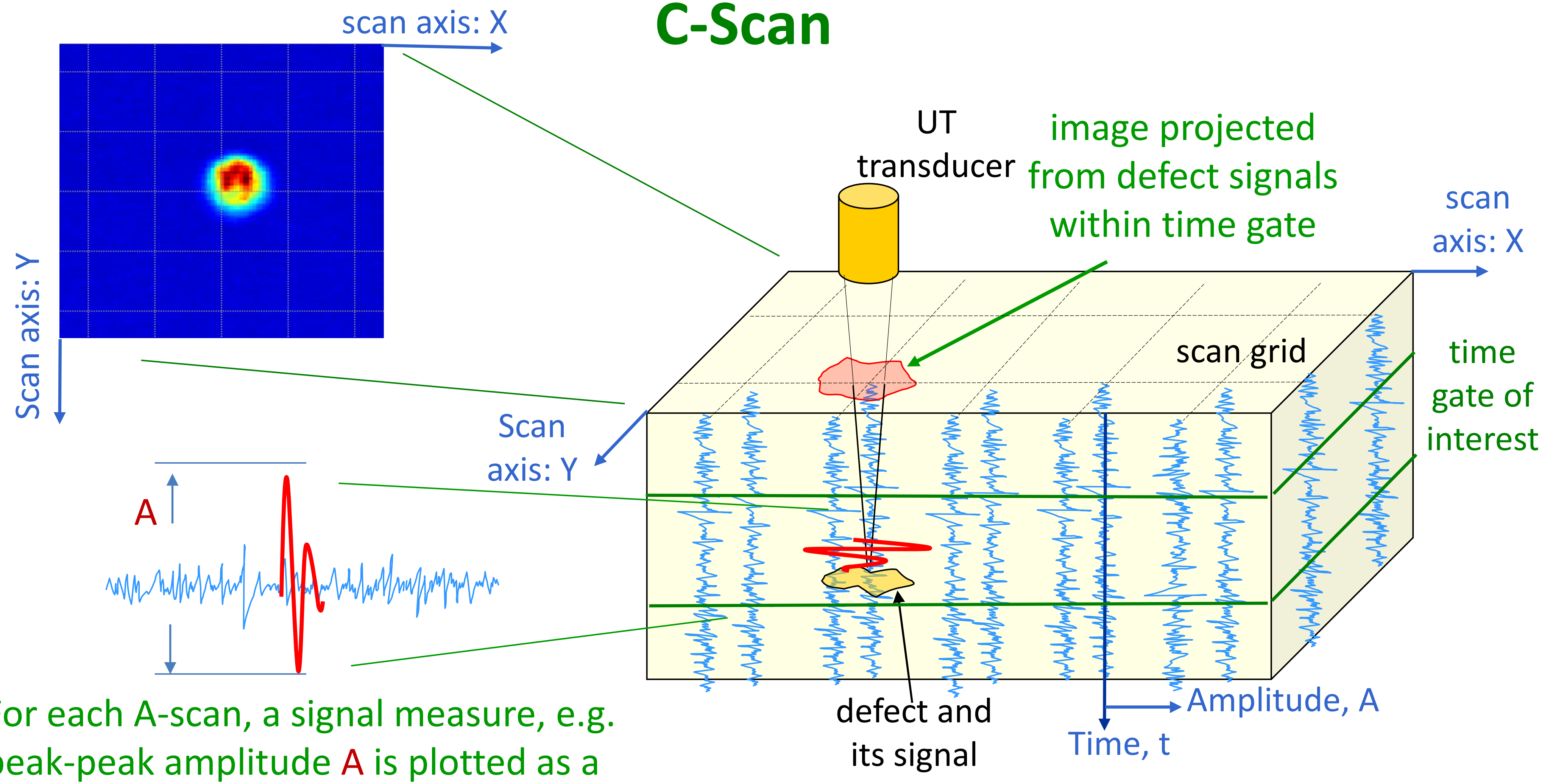


In contact mode, the initial pulse and front surface echo mix together, since transducer is directly on the front surface



Ultrasonic Testing (cont'd)

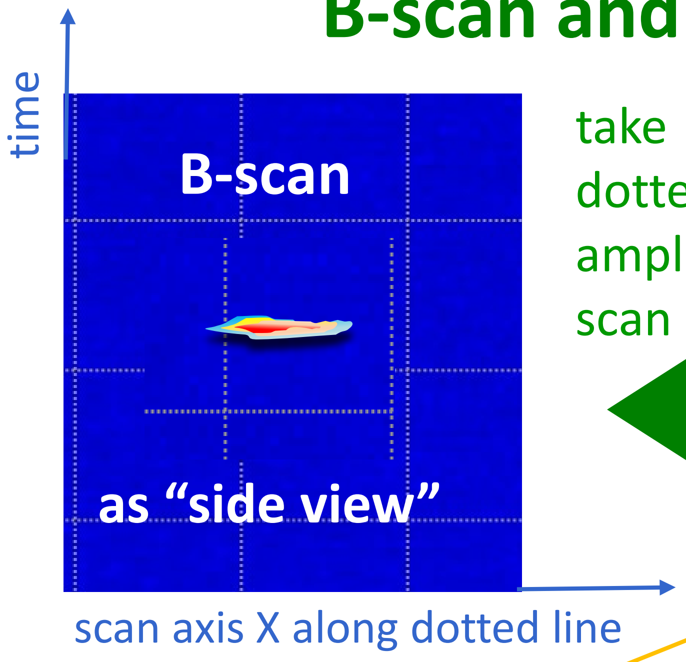
C-Scan



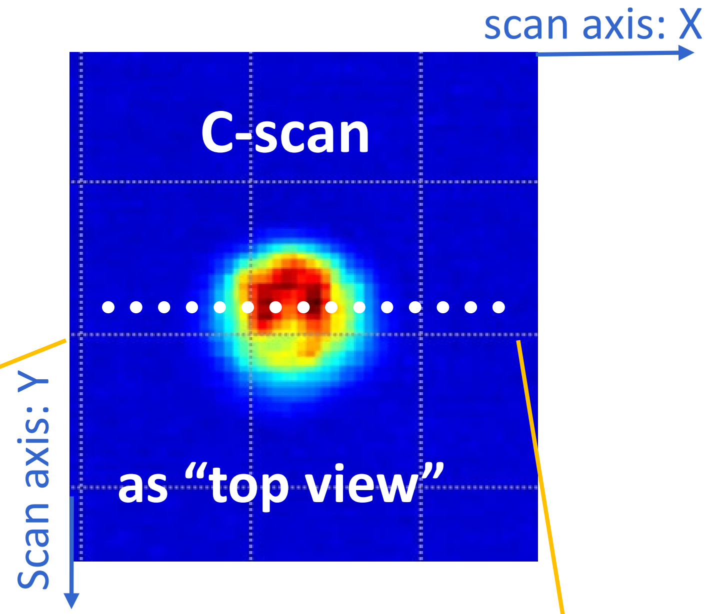
For each A-scan, a signal measure, e.g. peak-peak amplitude A is plotted as a pixel value in the C-scan image

Ultrasonic Testing (cont'd)

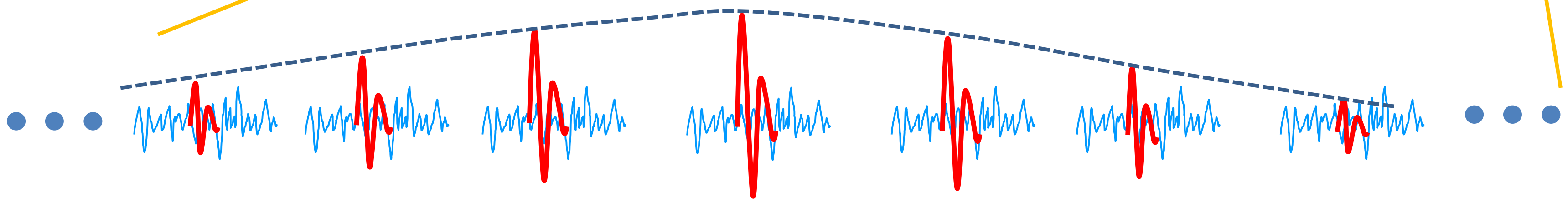
B-scan and Defect Amplitude profile



take every A-scan along the dotted line and plot the amplitude values of each A-scan as a vertical line of pixels



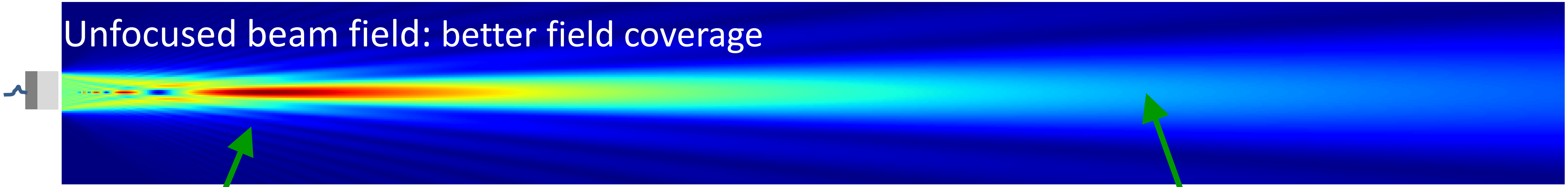
Defect amplitude profile



~ defect size (usually **overestimated**! why?)

Ultrasonic Testing (cont'd)
Transducer Specifications and Beam Pattern

Ultrasonic transducers are normally specified by its **frequency range**, **size** (diameter if spherically) and **focal length** (if of focus type). Collectively these specifications determine the behavior of a transducer and its beam field. Below show unfocused vs focused beam patterns as the ultrasonic pulse sweeps through the field:



Ultrasonic beam energy distributed more evenly throughout the beam "column"

the beam field will gradually spread out due to the so-called diffraction effect

Ultrasonic beam energy confined in the narrow focal zone

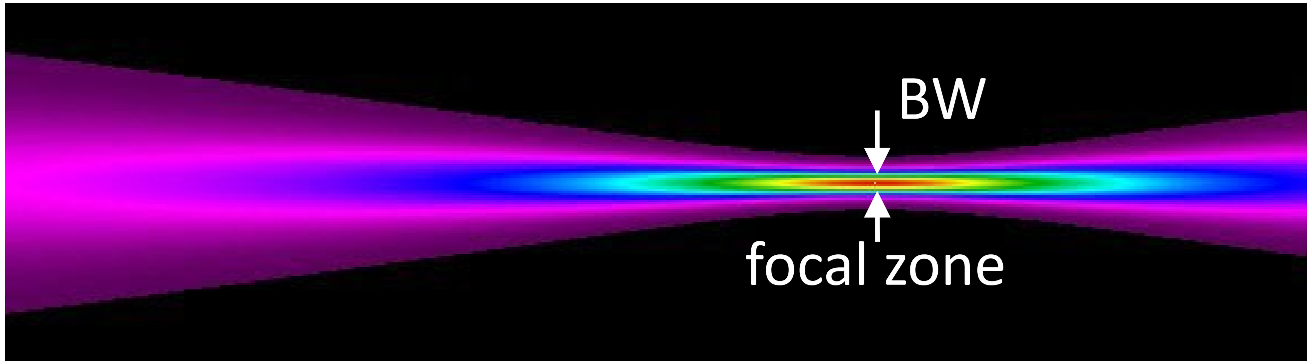
Ultrasonic Testing (cont'd)

Focused Beam Fields

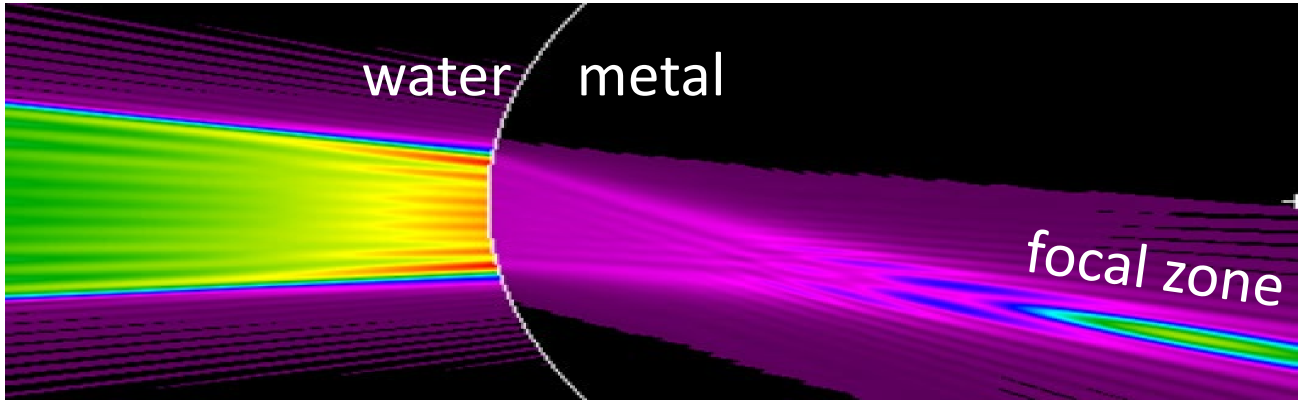
Note that the beam always has some width even at focus. The beam width BW at focal zone can be estimated by

$$BW = 1.02\frac{FV}{fD}$$

F=focal length; *V*=wave speed in the medium
f=frequency ; *D*=transducer diameter



The beam pattern across interface can be quite complicated. Shown on the right is a focused beam obliquely propagating through a curved water-metal interface in an immersion testing

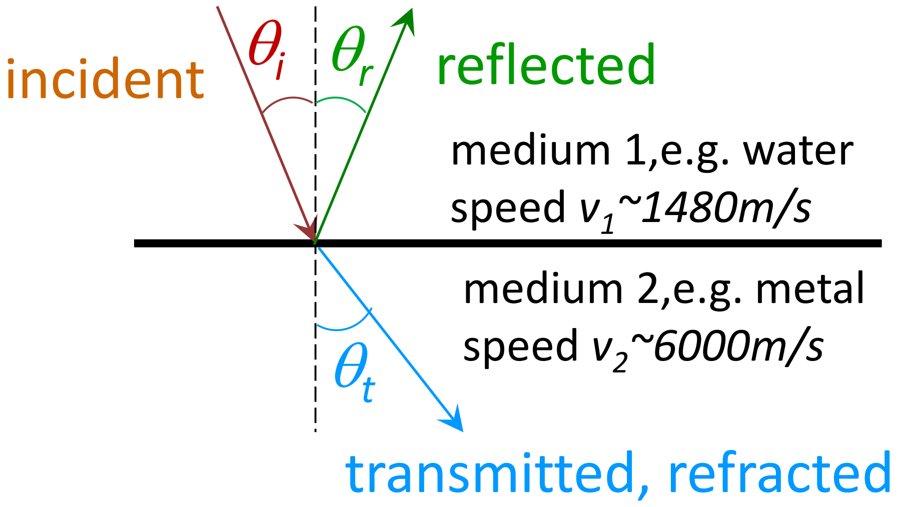


Ultrasonic Testing (cont'd)

- UT testing is governed by the principle of transmitting and/or reflecting mechanical waves at frequencies from kHz up to GHz
- In the plane of propagation, ultrasound can travel in longitudinal (L) and transverse (T) wave type. In L-wave, the medium particle vibrates back and forth along the same direction as the wave propagates, while in T-wave the particle vibrates perpendicularly to the wave direction. Each wave type travels at a specific speed in a given uniform isotropic medium
- When propagating through interface, ultrasound also follows Snell's law as in optics:

$$\frac{\sin\theta_i}{v_1} = \frac{\sin\theta_r}{v_1} = \frac{\sin\theta_t}{v_2}$$

e.g. for an incident angle θ_i at 10°, the reflected angle θ_r is also 10° while the resulting refracted angle θ_t is 44.75°



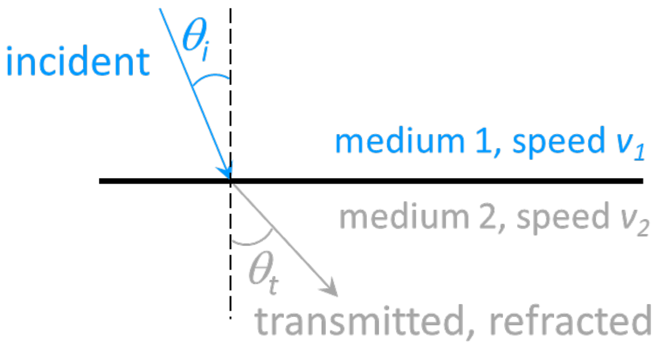
Mode conversion omitted here

Ultrasonic Testing (cont'd)

Time-of-flight

$$\Delta t = \Delta t_1 + \Delta t_2 = \frac{2Z_1}{v_1} + \frac{2Z_2}{v_2}$$

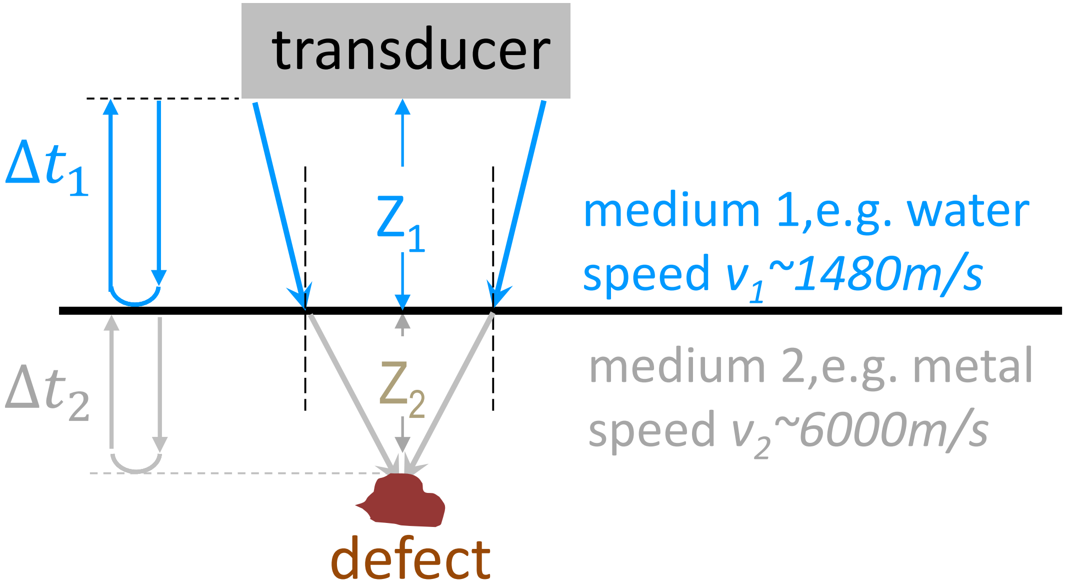
For the water-metal interface shown here, suppose defect depth Z_2=2cm and water path Z_1 = 4cm, then time-of-flight Δt = 60.72 microsecond = 60.72 x 10^{-6} second



Focal law

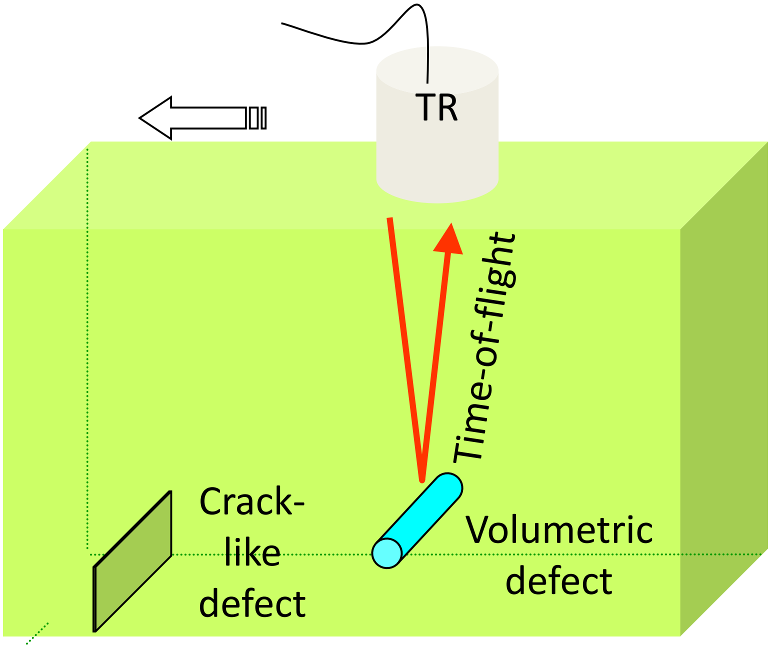
$$F = Z_1 + \frac{v_2}{v_1} Z_2$$

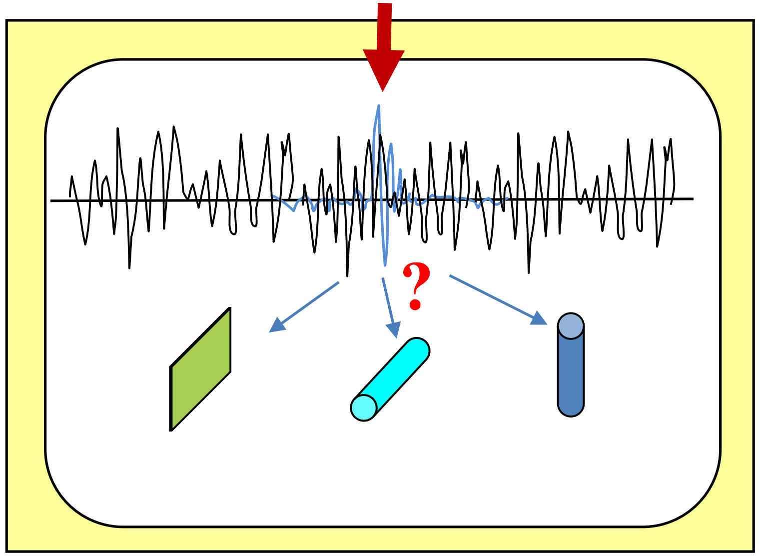
Suppose the transducer focal length F is 5". To best focus on the defect in the metal at depth Z_2=1" then water path Z_1 needs to be set ~1"



Ultrasonic Testing (cont'd)
Echo Dynamics

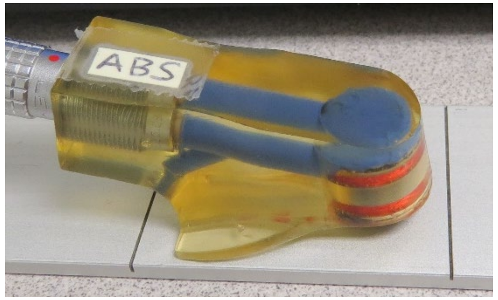
- Determine the defect location from transducer position with respect to the sample
- Estimate depth from ½(wave speed)x(time-of-flight)
- Estimate defect size from amplitude profile (p. 17)
- Deduce defect type (volumetric vs. crack-like) from their rates of change in amplitude and phase profiles and their absolute signal amplitudes

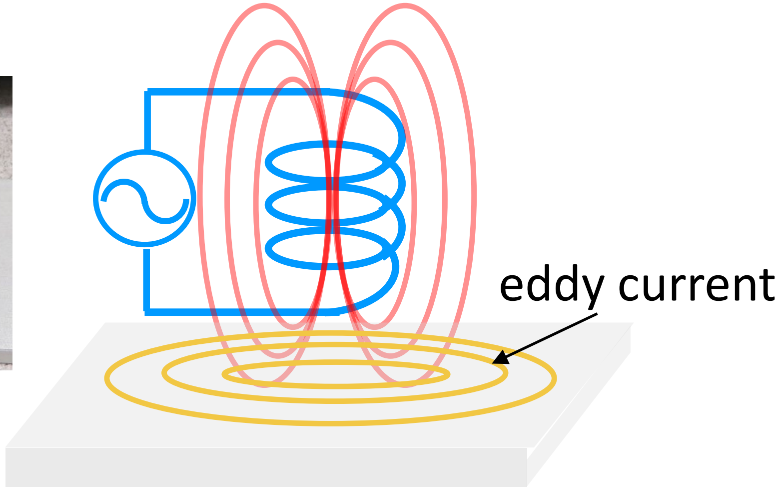


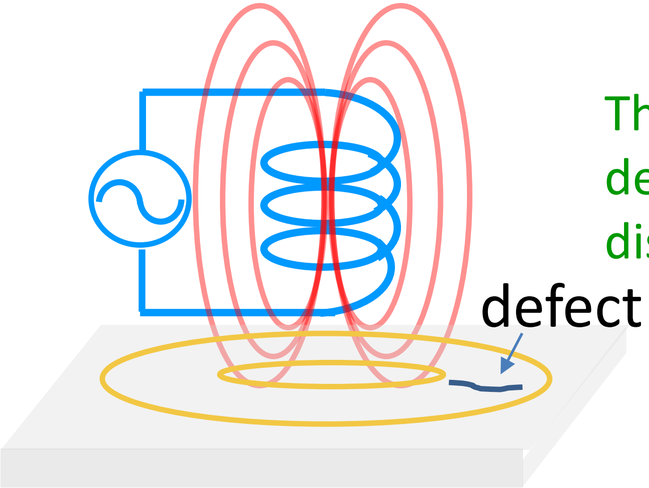


Eddy Current Testing

- Eddy current (EC) testing is a contact electromagnetic technique. It works by applying alternating electric current to coil roll to generate a changing magnetic field, which in turn generates EC in the conductive test sample
- The presence of defect interrupts the flow of EC and hence its strength. By monitoring this strength change, EC can then be used as a viable tool for flaw detection



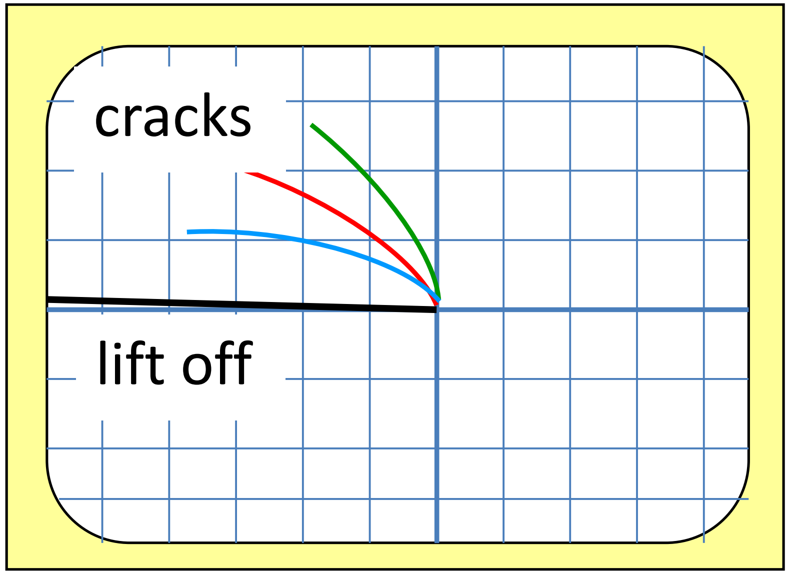


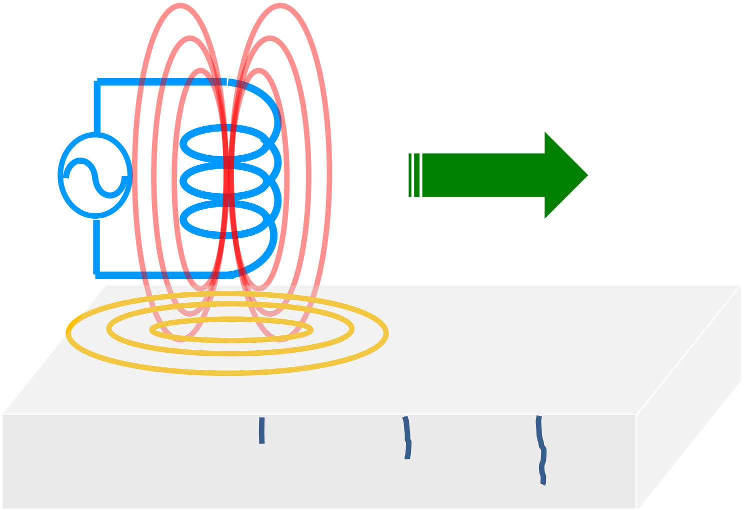


The presence of defect (crack) disturbs the EC field

Eddy Current Testing (cont'd)

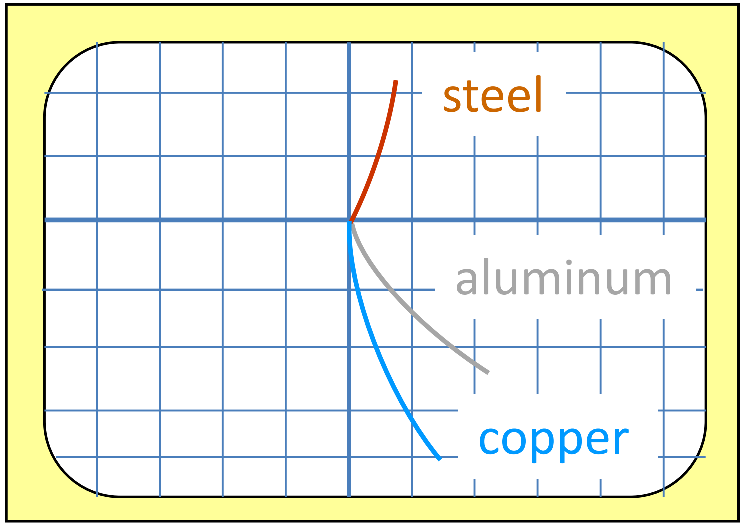
- EC responses are typically plotted on the "impedance plane" whose horizontal axis denotes the resistance R and vertical axis represents the inductive reactance X_L
- During testing an EC system requires frequent "balance" or "zero out" which is done by taking measurement from a defect-free sample of the same material. EC responses can also be calibrated via "lift-off", i.e. moving the coil on and off the sample

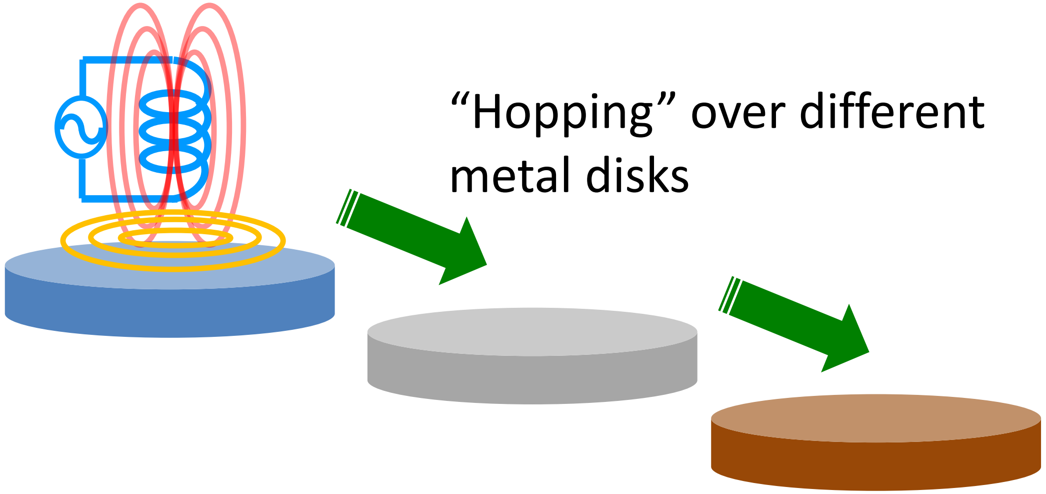




Eddy Current Testing (cont'd)

- The EC probes seen so far are single coil known as "absolute probe" which is good for detecting various crack situations
- Absolute probe is also sensitive to electrical conductivity and magnetic permeability of materials, which makes it very useful for sorting out these materials
- Here the balance is directly done in the air

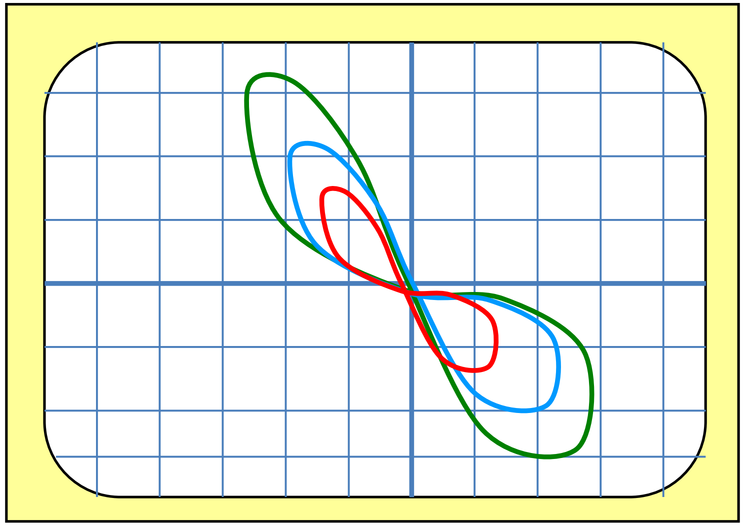


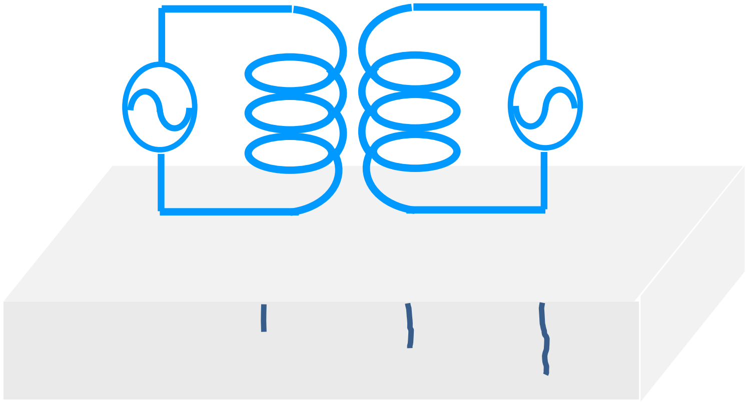


"Hopping" over different metal disks

Eddy Current Testing (cont'd)

- Another common EC probe type is "differential probe" which consists of two coil elements and the system response measures the difference between the two elements
- Differential probe is good for detecting small cracks and is relatively insensitive to lift-off and temperature variations
- The so-called "butterfly" pattern is notably differential probe 's unique impedance response



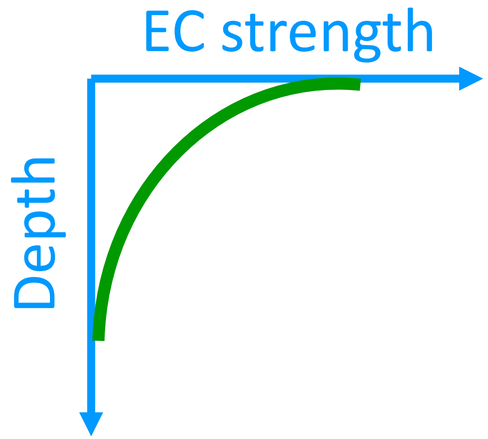


Eddy Current Testing (cont'd)

- Eddy current density decreases exponentially with depth due to the skin effect: EC penetration depth in conductor is governed by

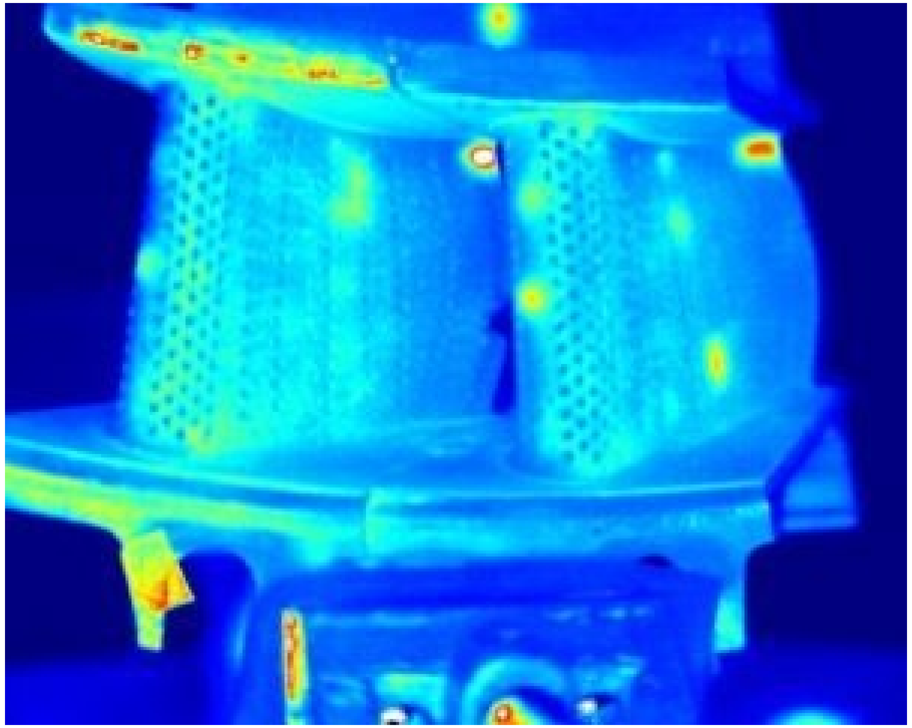
$$\delta \approx \frac{1}{\sqrt{\pi f \mu \sigma}}$$

where δ is the penetration depth, f is the frequency, μ is the magnetic permeability of the material, and σ is the electrical conductivity of the material



Other NDE Techniques: Thermography

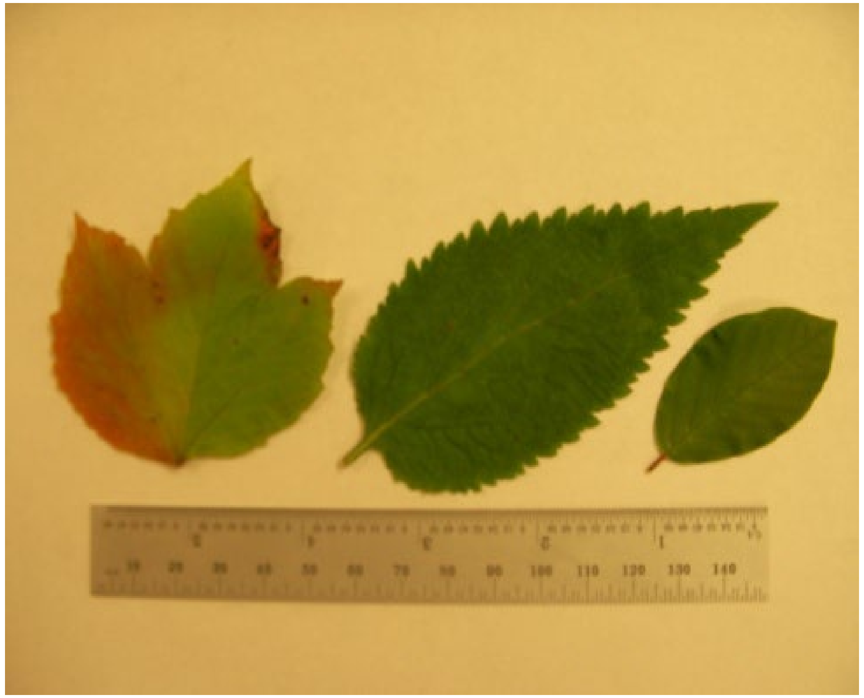
Thermal image of turbine blades

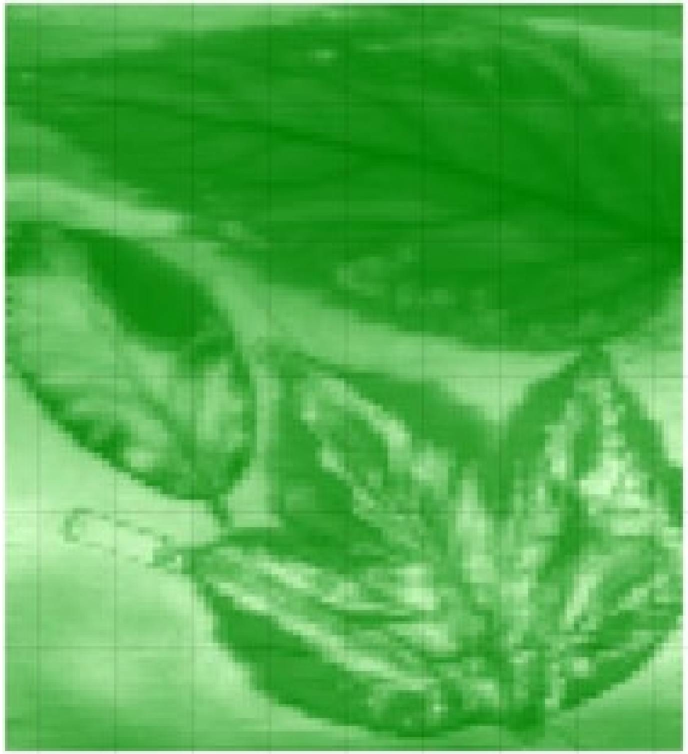


Courtesy: Steve Holland, Center of NDE, ISU

Other NDE Techniques: Terahertz Imaging

THz "anatomy" of plant leaves

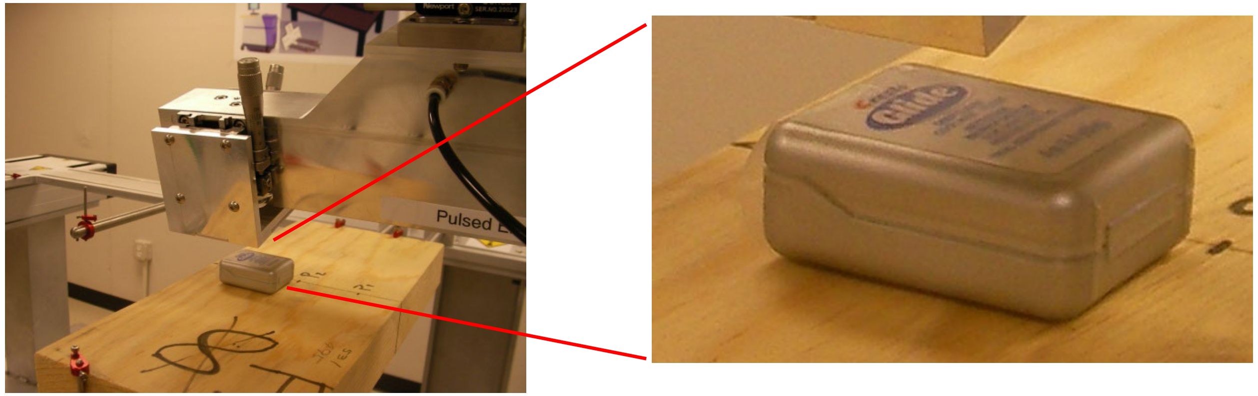




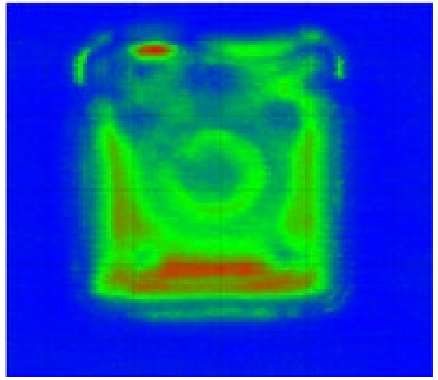
Courtesy: Thomas Chiou, Center of NDE, ISU

Other NDE Techniques: Terahertz Imaging (cont'd)

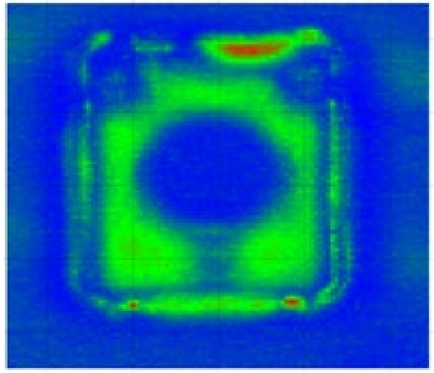
"Slicing" through a floss box



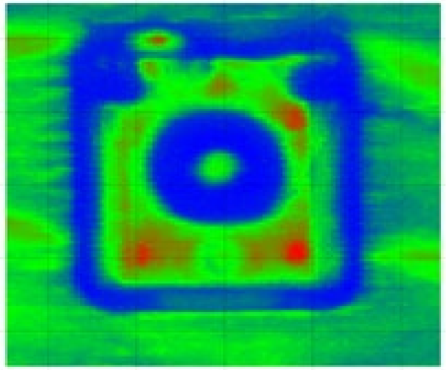
top surface



below top surface



middle floss core

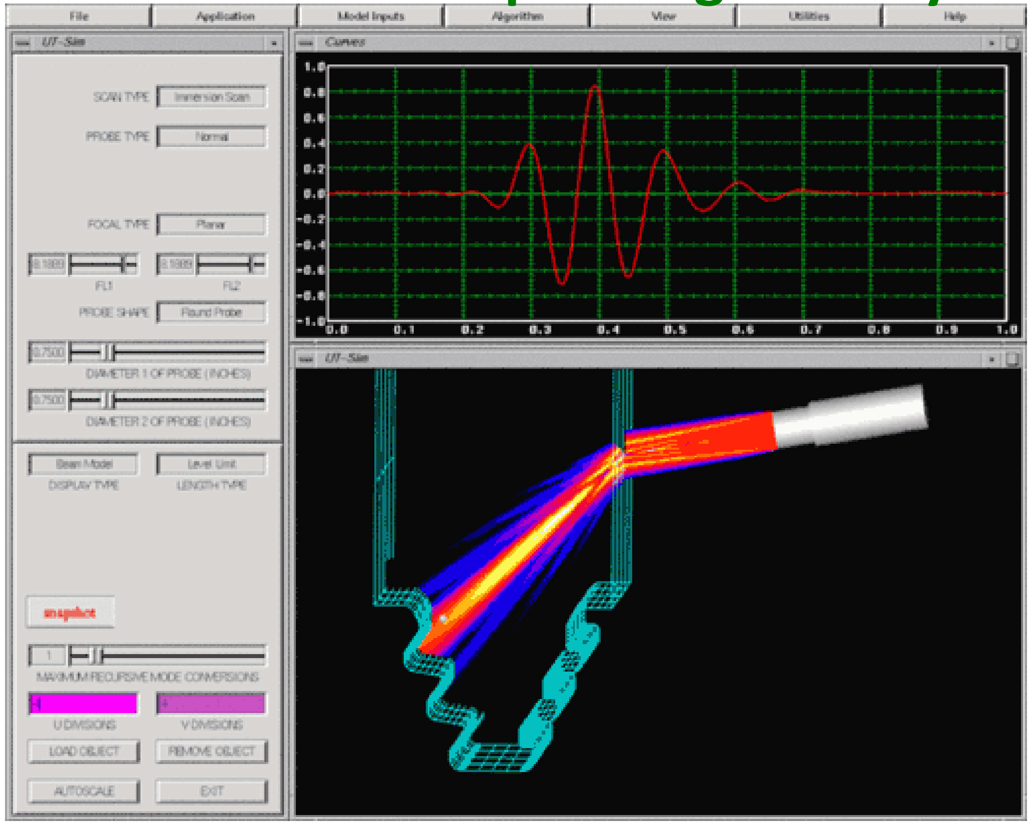


Courtesy: Thomas Chiou, Center of NDE, ISU

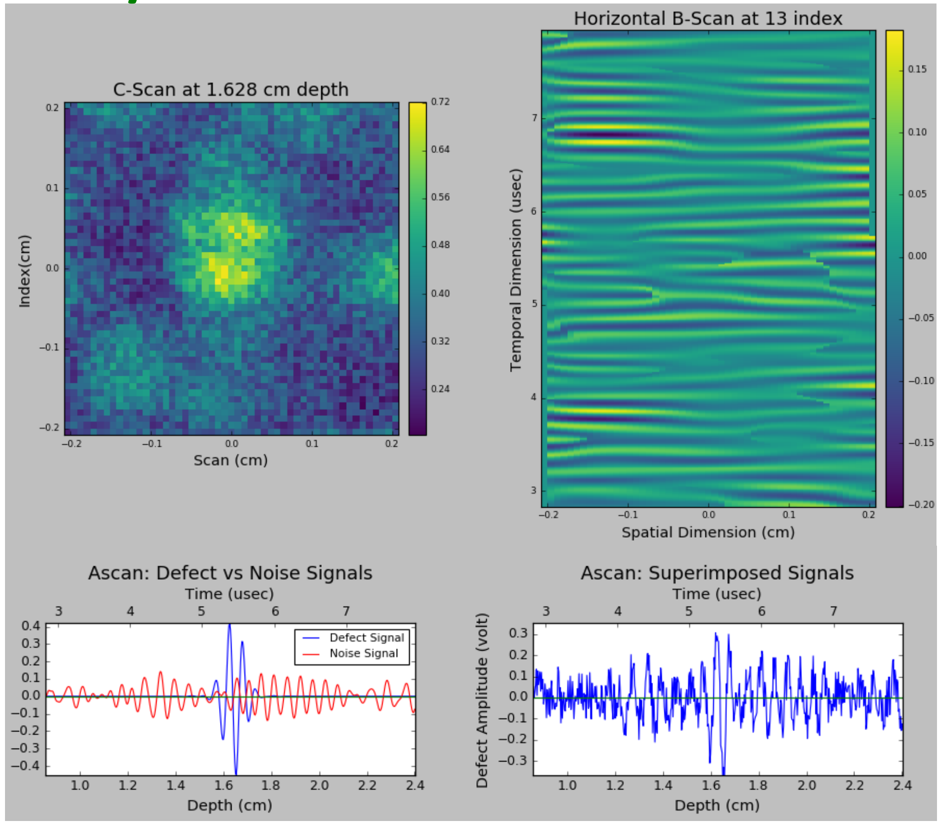
NDE Analysis Tool: Simulations by Modeling

Simulation enables virtual inspections which are cost-effective and efficient. Shown are two CNDE ultrasonic simulators in action.

UTSim on complicate geometry



UTS/N on microstructural noise

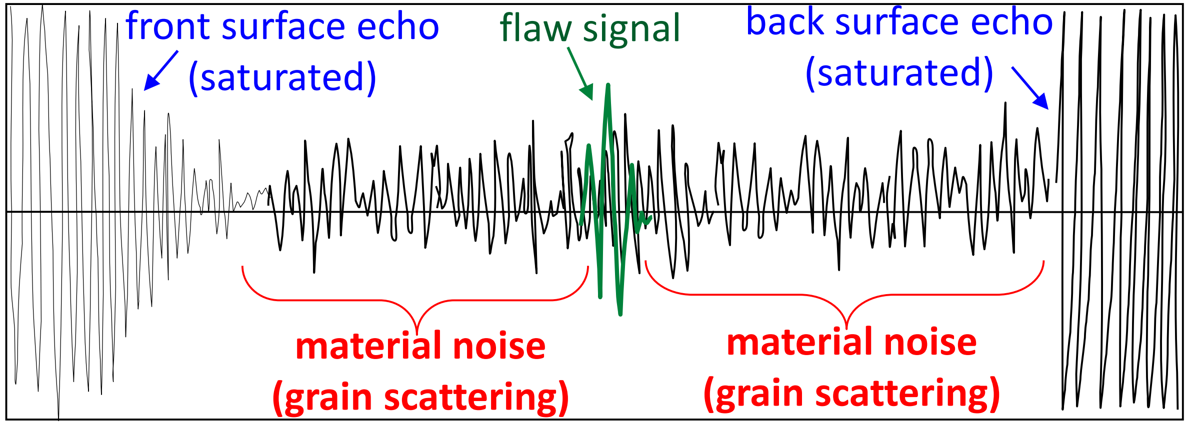


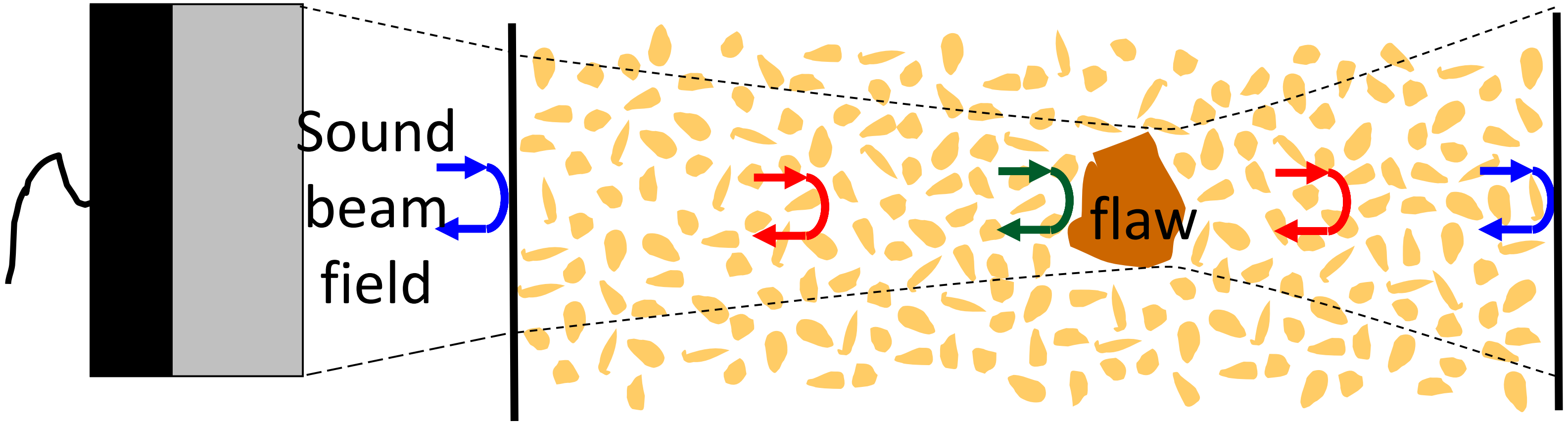
Courtesy: Thomas Chiou, Center of NDE, ISU

Motivations
Ultrasonic Modeling: the *Missing* World

Ultrasonic signal traces as seen on an oscilloscope

Ultrasonic flaw signal modeled





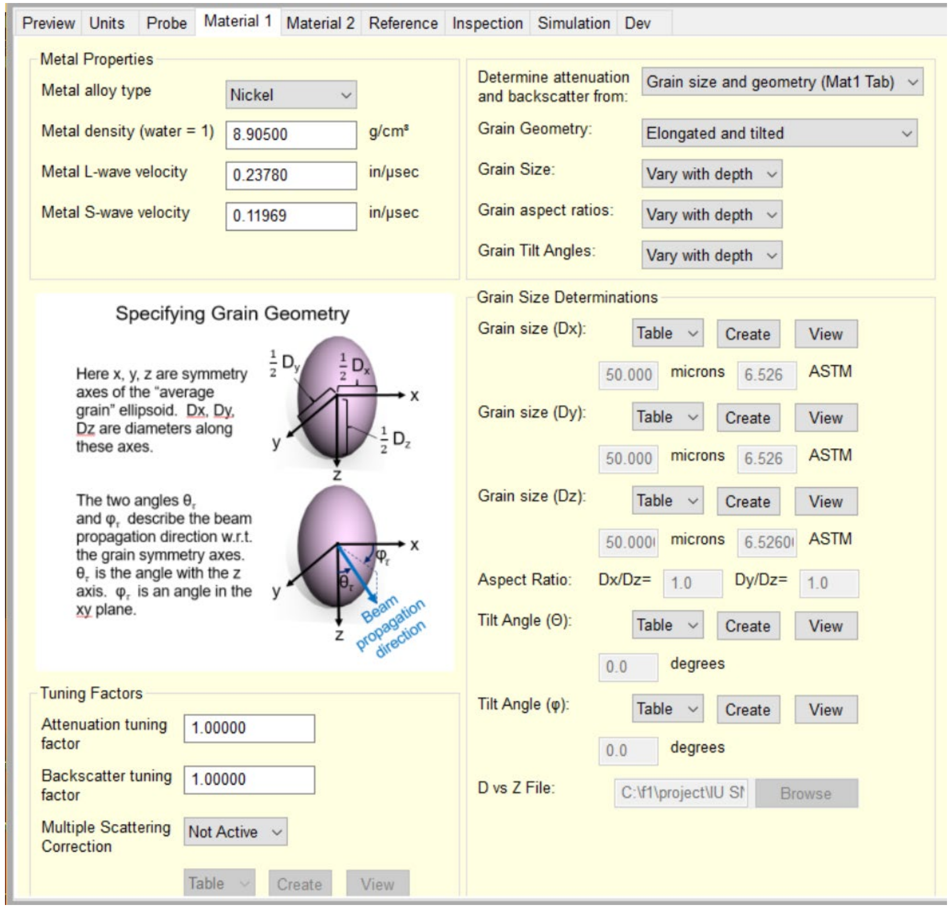
Transducer

Grain structures in e.g. titanium alloy

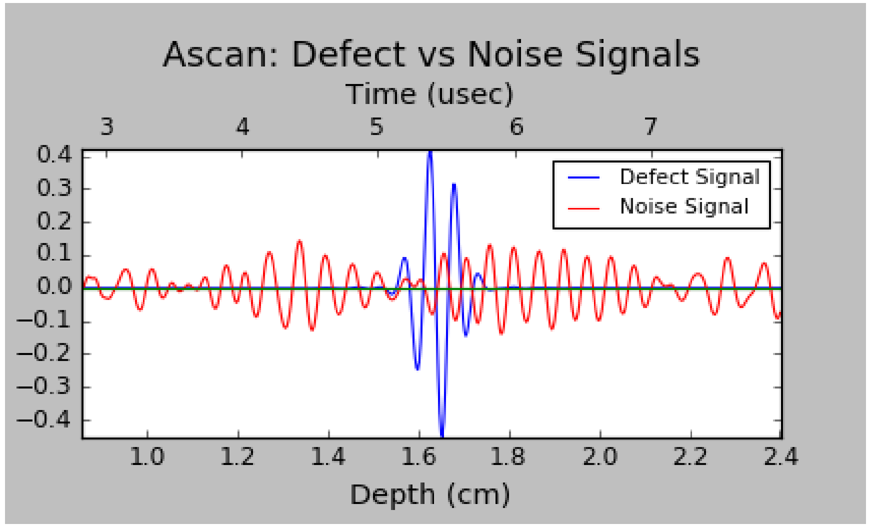
UT S/N Simulator In Action

In this lab, you will play with the UT S/N simulator to optimizes defect detectability against microstructural noise

GUI makes modeling easy



Signal-to-noise ratio maximized

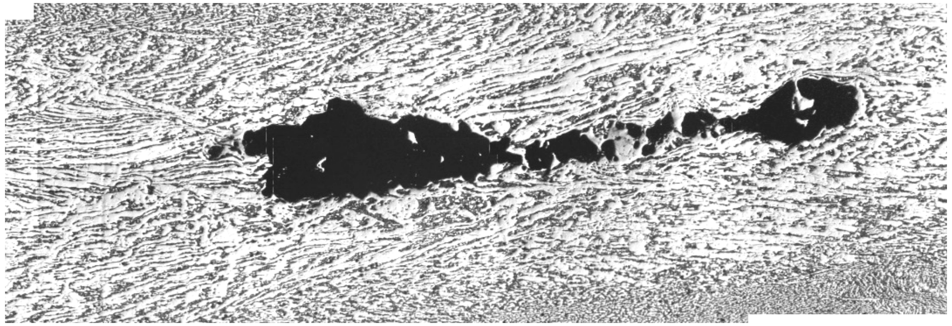


Signal-to-noise ratio (SNR)

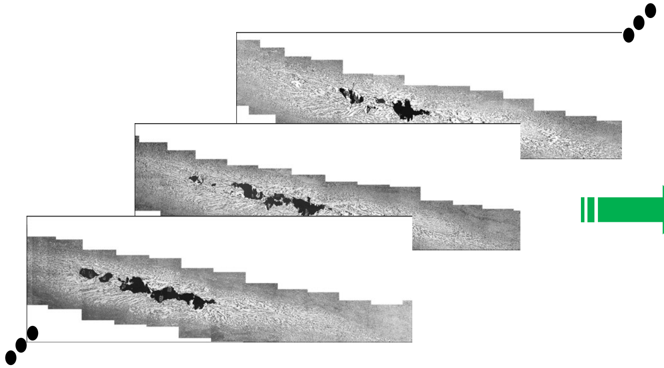
$$\approx \frac{\textbf{peak defect amplitude}}{\textbf{peak microstructural noise}}$$

Real-World Application of Ultrasonic Modeling

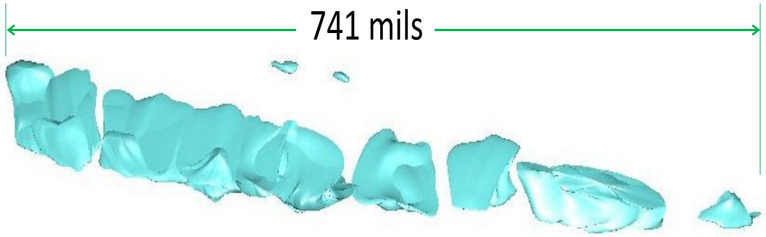
Detection of hard-alpha inclusion in titanium alloys



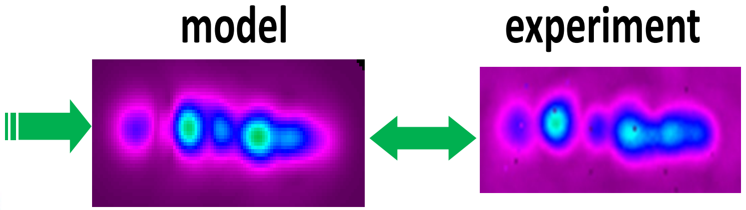
A joint research efforts of major jet engine makers and ISU-CNDE funded by FAA over a decade



Each cross-sectional profile composed from 25-40 metallographs



11 flaw parts reconstructed from 54 boundary traces in 16 cross-sectional profiles



C-scan peak amplitude accurate within 11% or 0.92 dB

Courtesy: Thomas Chiou, Center of NDE, ISU

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