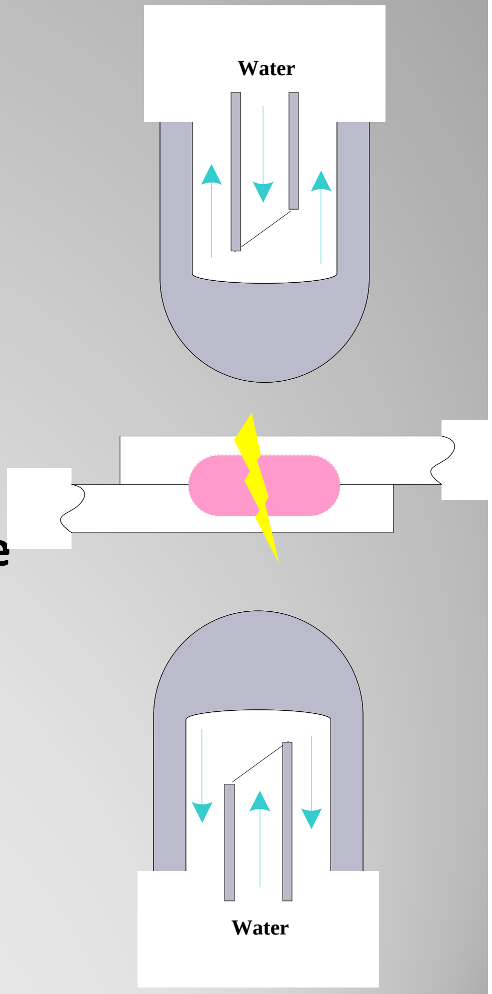
Part 2

Industrial applications of acoustic microscopy

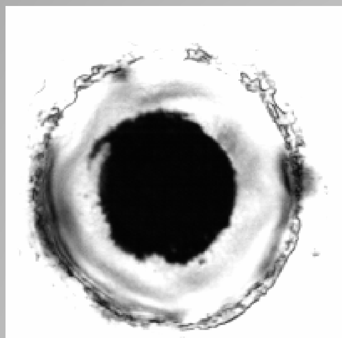
Ultrasonic inspection of resistance spot welds

Resistance Spot Welding

- One of the most commonly used joining methods for sheet metals in the automotive industry
- Uses joule heating to produce heat from electric current flow
- Periodic destructive tests are often used to inspect the quality of a spot weld: peel tests and chisel tests
- Non-destructive off-line methods are also available to inspect spot welds
- Both have disadvantage of having to remove the part from the production line
- An advanced non-destructive in-line ultrasonic system has been developed which can evaluate spot welds in real-time

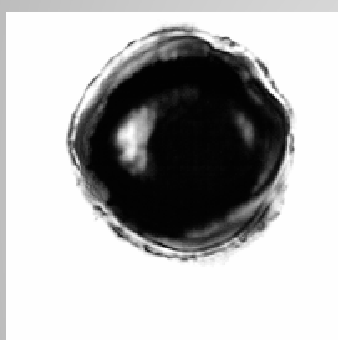


Spot Weld Inspection with SAM

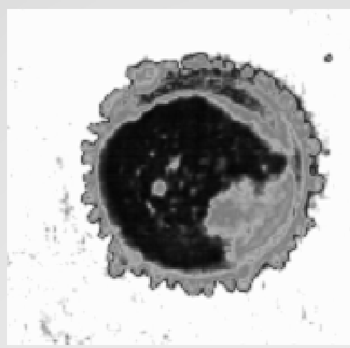


Measurement of weld diameter

Detection of inclusions

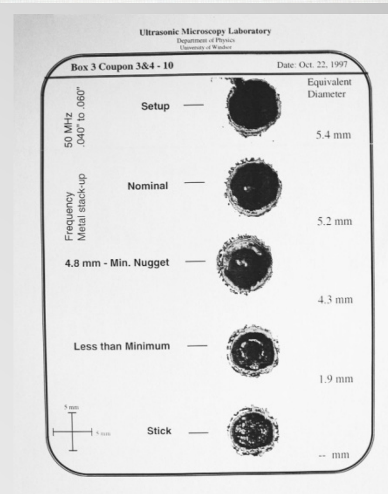


Corona effect



Stick welds

Certification of weld coupons



Inspection of Laser Stitch Welds

Laser stitch welds acoustical images

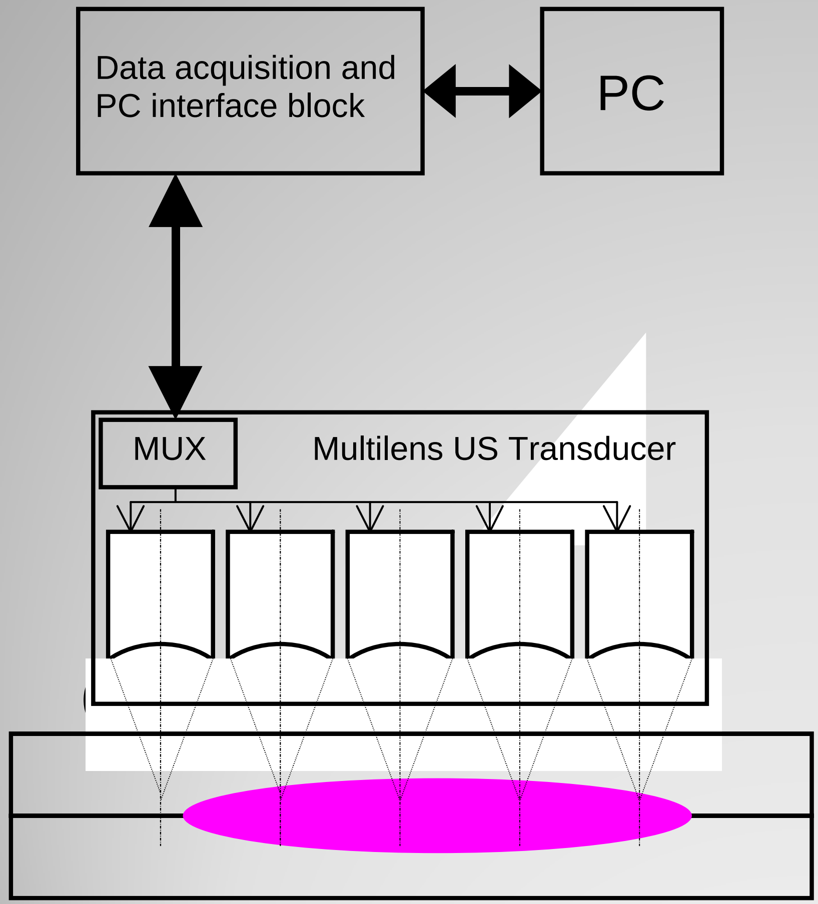
0.75 mm thick (left) and 1mm thick (both right) steel plate with approximately 3 mm width welds

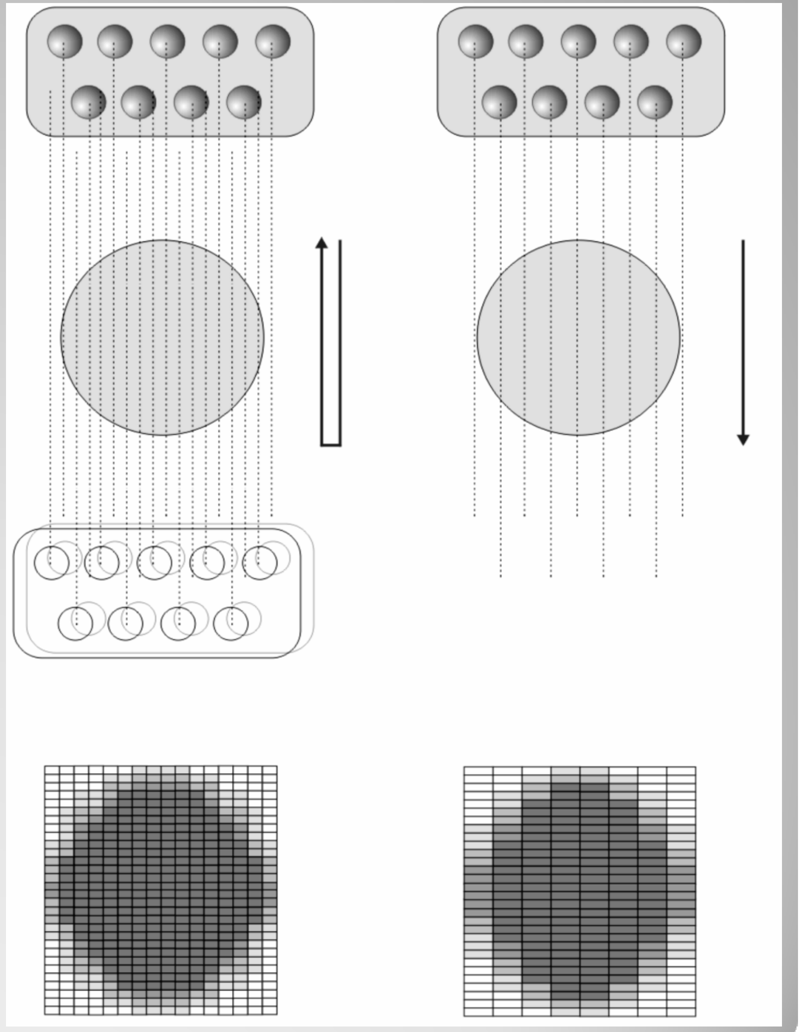
Detectable imperfections:

- Insufficient length
- Seam interruption
- Lack of fusion
- Pin hole existence

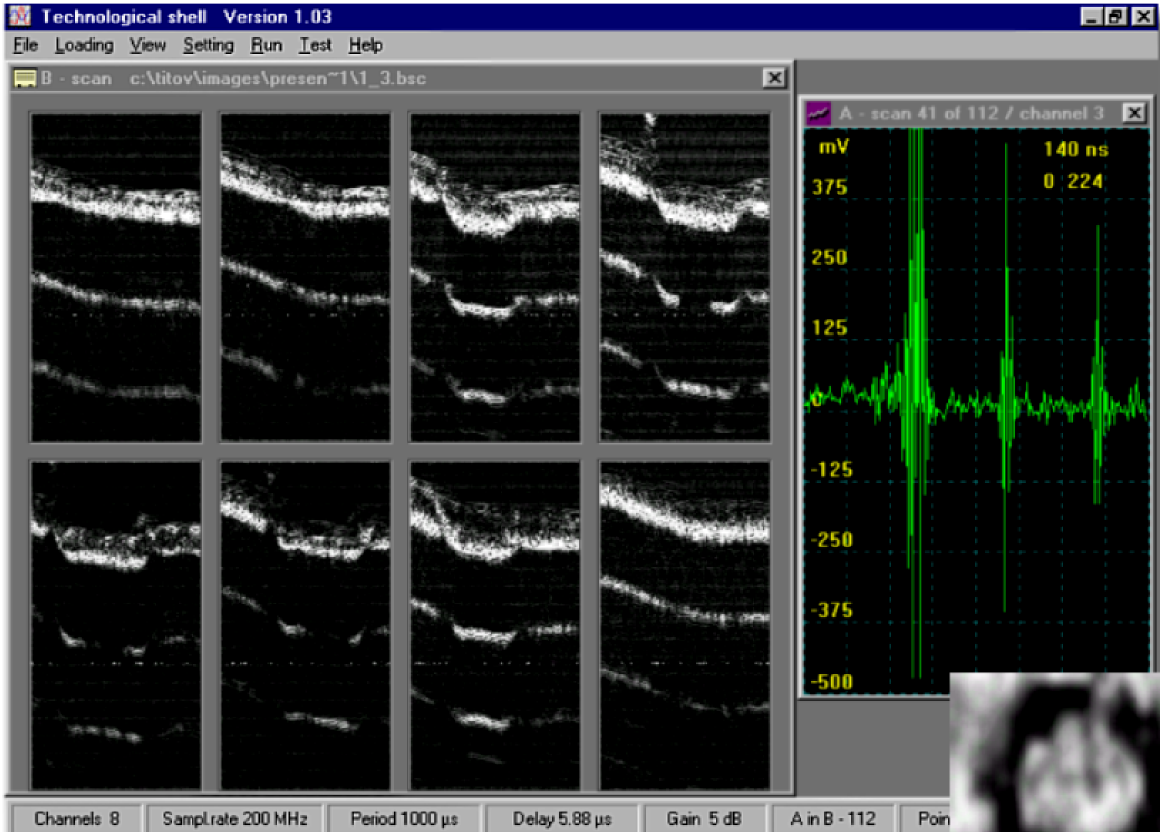
Portable Hand-Held Imaging Solutions

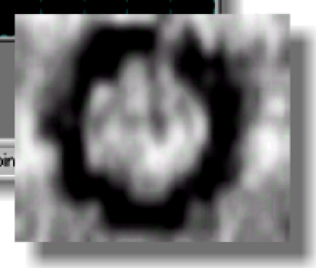
Multi-Lens System

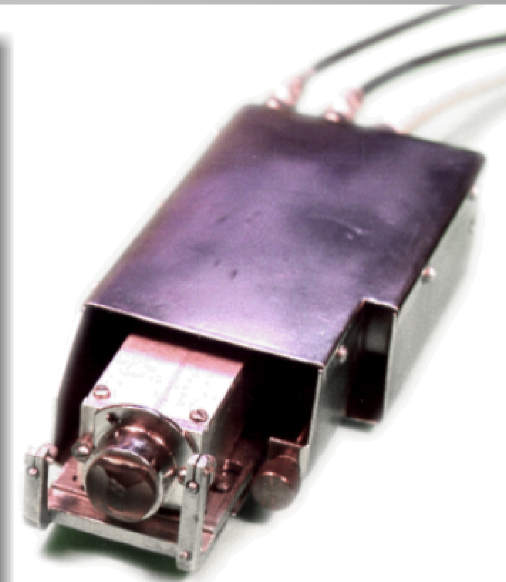




Multi-Lens System





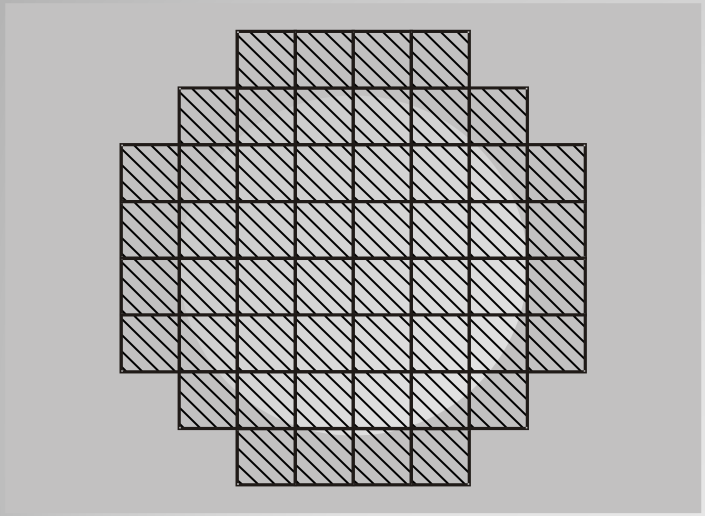


2D Matrix Array Technology

Resistance Spot Weld Analyzer

- A portable, easy in operation ultrasonic device for assessing the quality of resistance spot welds
- Ultrasonic sensor is the latest generation of matrix transducer technology
- Provides internal image of the weld
- Automatically estimates the nugget diameter and surface indentation
- Features automatic setup and calibration

From Single-Element Probes to 2D Matrix Transducers



Matrix transducer

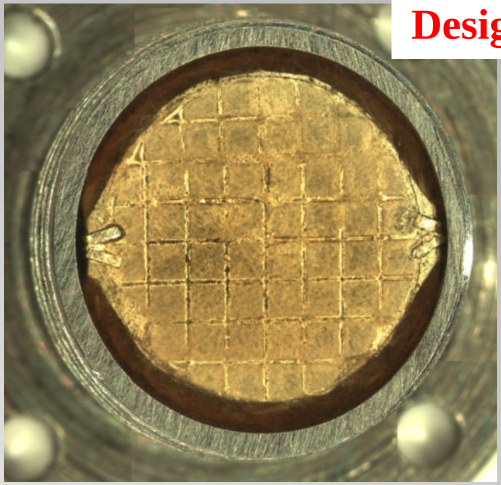
uses electronic scanning to obtain the 3D image

– *Pros:* No moving parts, real-time imaging and nugget size estimation, hand-held, simple in operation

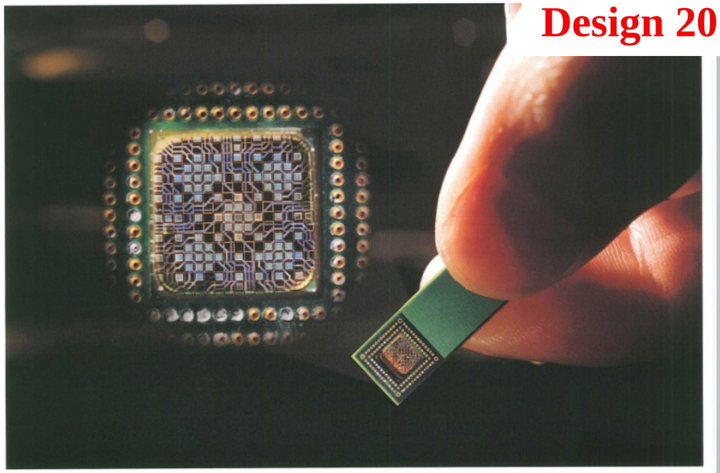
– *Cons:* Low resolution, probe is larger than that in single-transducer devices

2D Matrix Array Transducer System

- Number of channels: 52
- Central frequency: 15 MHz
- Bandwidth: 15 MHz
- Wavelength (water): 90 µm
- Mode: multiple A-scans, C-scan
- Various compensation methods and C-scan filtering algorithms
- Template calibration setup for 8x8 matrices



Design 2002



Design 2012

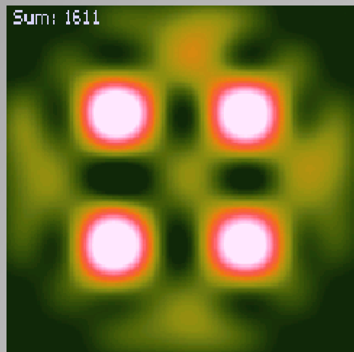
2D Matrix Array

- The RSWA's sensor is a unique matrix transducer designed specifically for spot weld testing
- Unlike phased arrays, commonly used in medical ultrasonic devices, this probe has 52 channels that work independent from each other

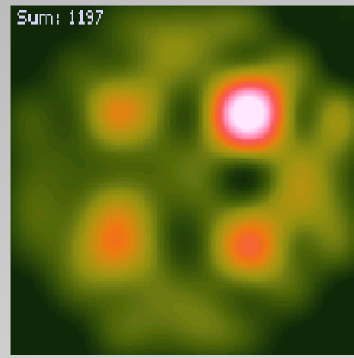
Parameters:

- **8×8 matrix**
- **52 independent elements**
- **1.25 mm element size**
- **15 MHz central frequency**
- **2 m cable with 52 coaxes**
- **Replaceable delay line**

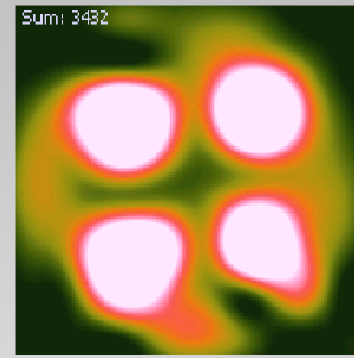
Depth Sensitivity



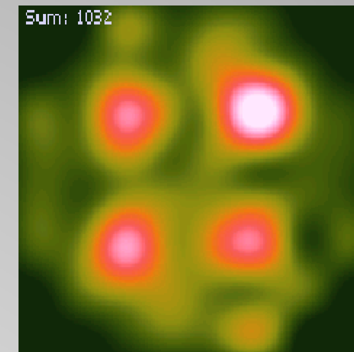
Ø 1 mm,
Depth: 1; 1.5; 2; 2.5 mm



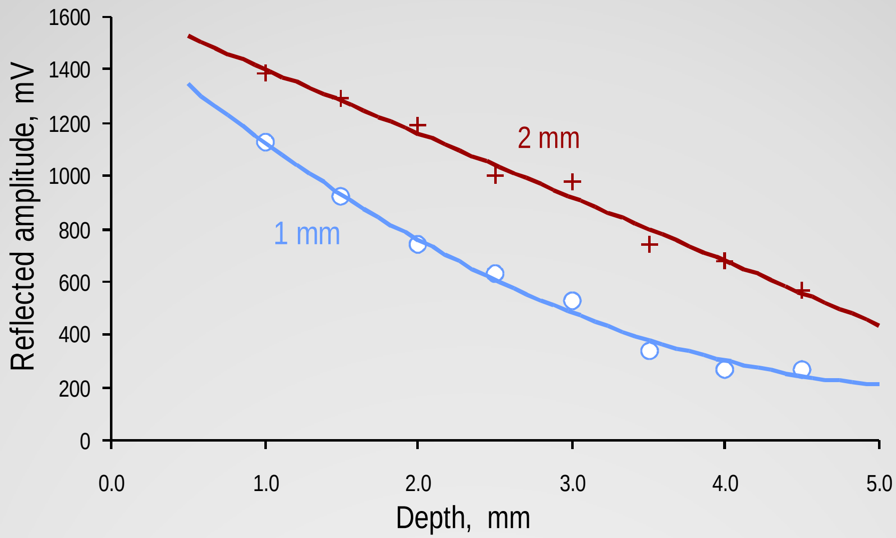
Ø 1 mm,
Depth: 3; 3.5; 4; 4.5 mm



Ø 2 mm,
Depth: 1; 1.5; 2; 2.5 mm

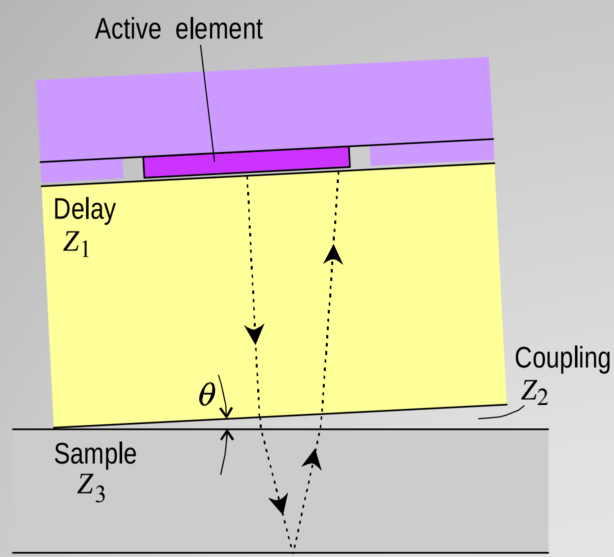


Ø 2 mm,
Depth: 7; 7.5; 8; 8.5 mm



Tilt Compensation

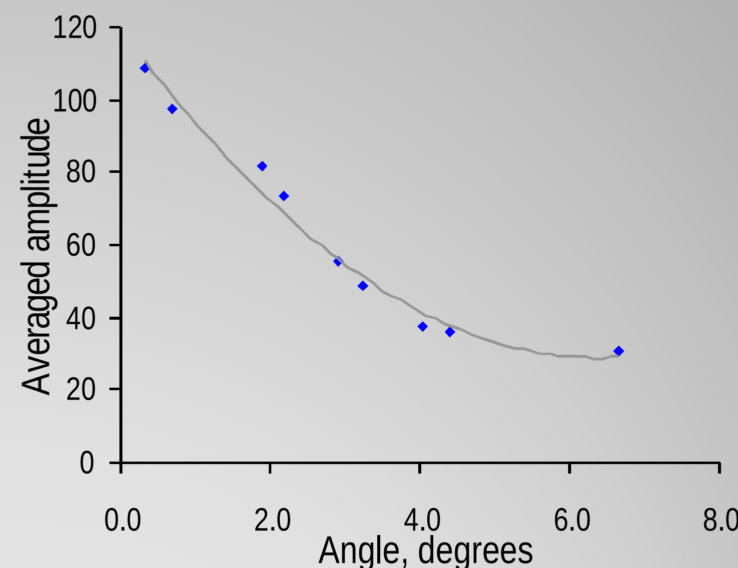
Effect of refraction of the beam
on a tilted interface



$$\theta = \arcsin(1.4/ka)$$

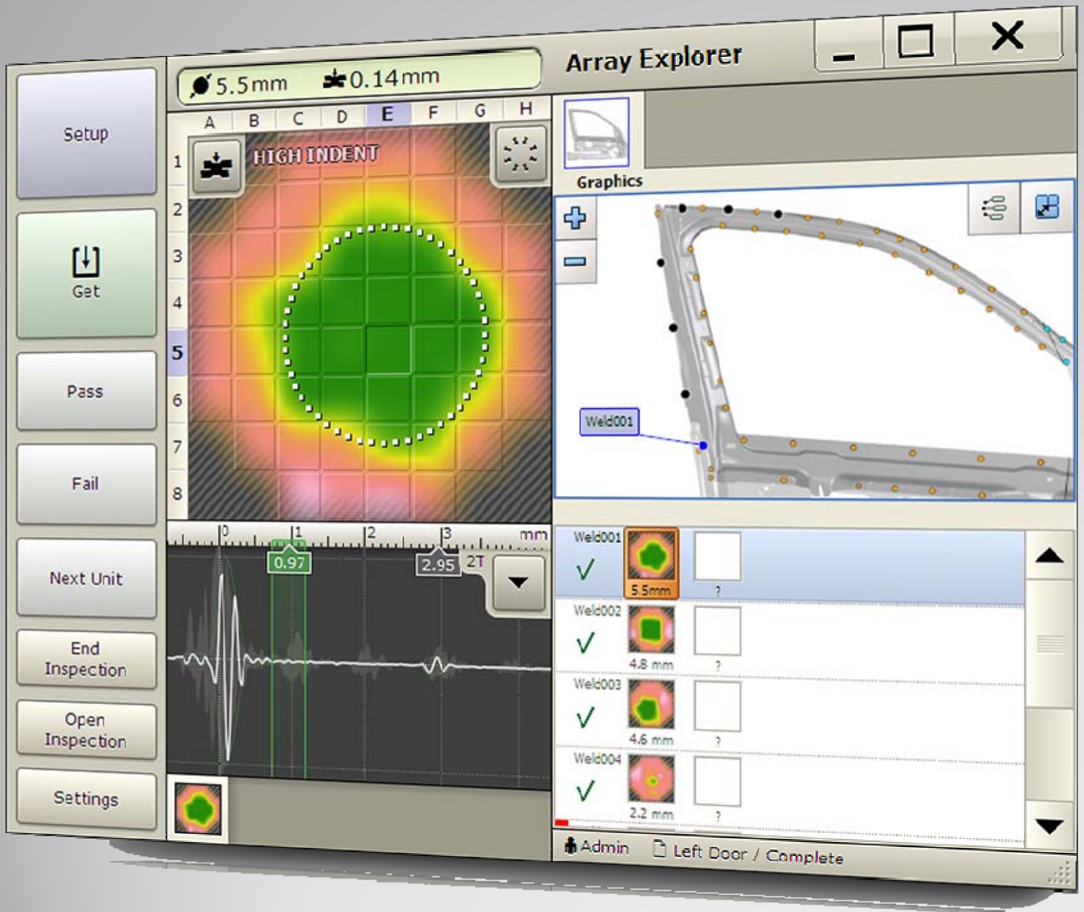
$$D_{123} = \frac{D_{12} D_{23} e^{-jk_2 h}}{1 - R_{21} R_{31} e^{-j2k_2 h}}$$

Transmitted amplitude vs. tilt



D_{ij} and R_{ij} are the corresponding, transmission and reflection coefficients
k_2 is the wave number of the layer
h is the thickness of the layer
indices 1 trough 3 point respectively to the delay, coupling medium and object

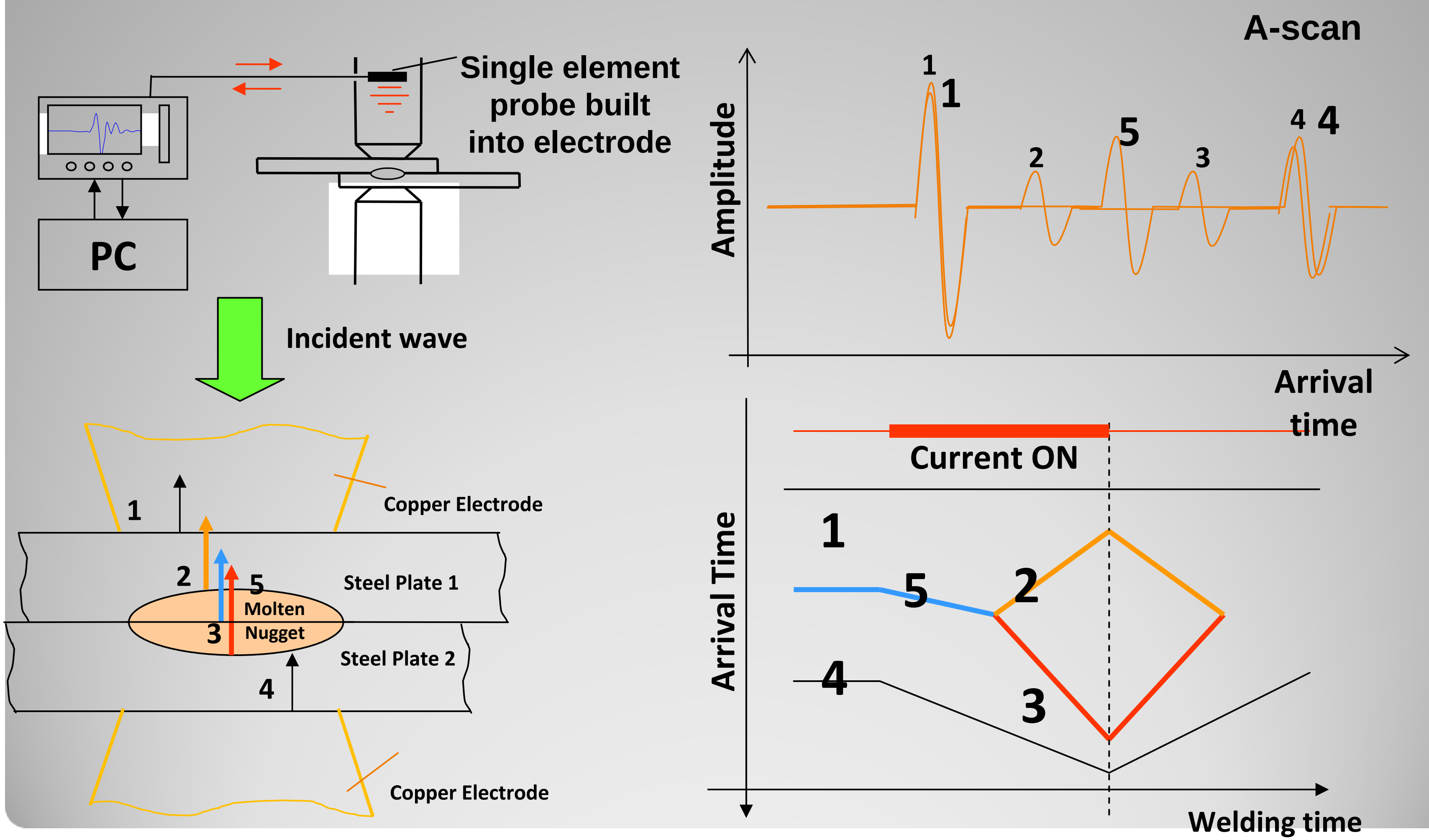
Reporting software



- The ultrasonic representation of a weld's internal structure is conveniently displayed on the screen as a color coded image
- The software displays the estimation for nugget diameter, surface indentation, and other parameters
- The automatic setup procedure simplifies RSWA operation

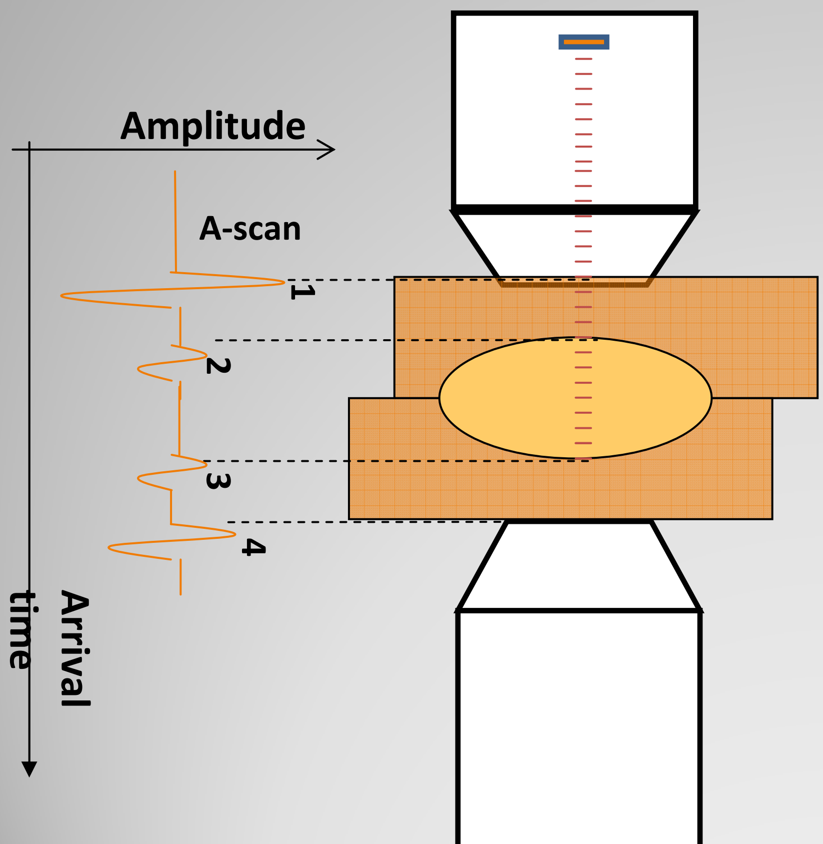
Ultrasonic Linear Phased Array System for Real-time Imaging Quality Monitoring of Resistance Spot Welds

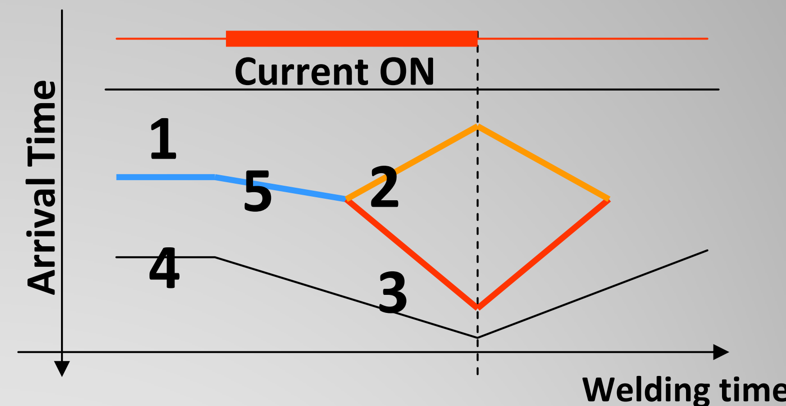
Advanced In-line System

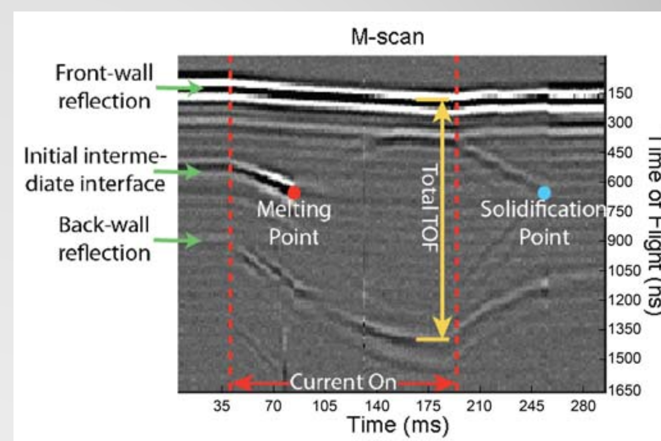


M-scan Formation

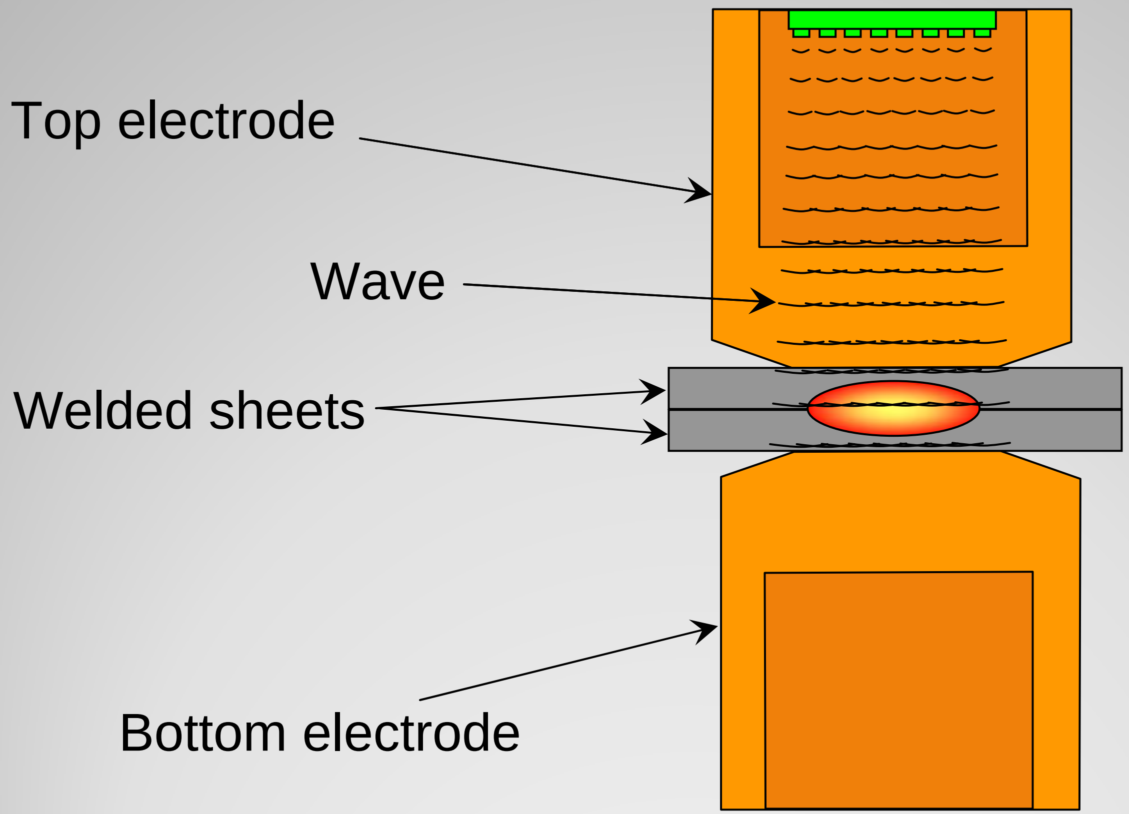
- M-scan: Combination of A-scans through time
- Every column in the M-scan represents a single A-scan





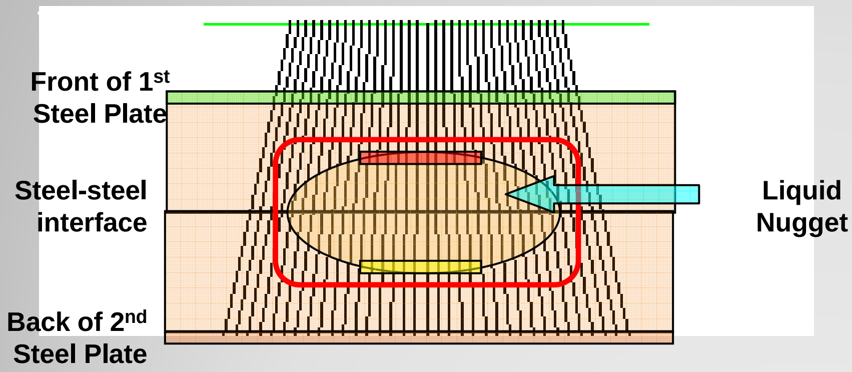


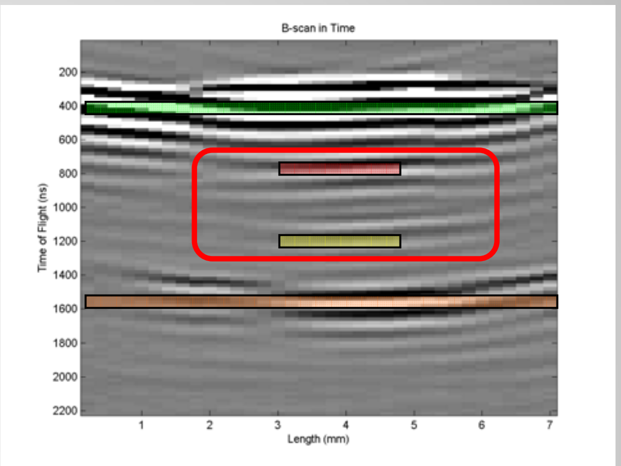
Array: Reflection method



B-scan Formation

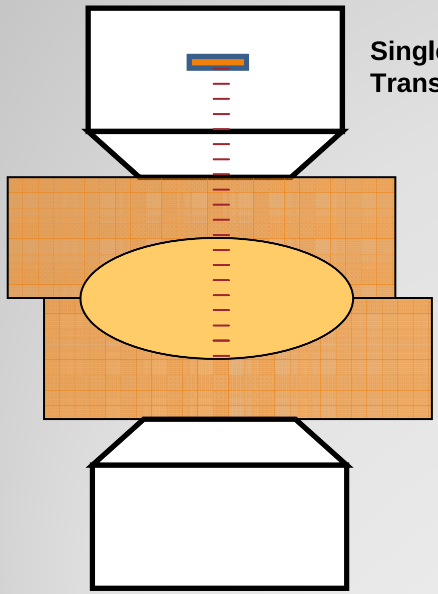
- B-scan: Combination of A-scans which form a cross sectional view
  - Every column in the B-scan represents a single A-scan

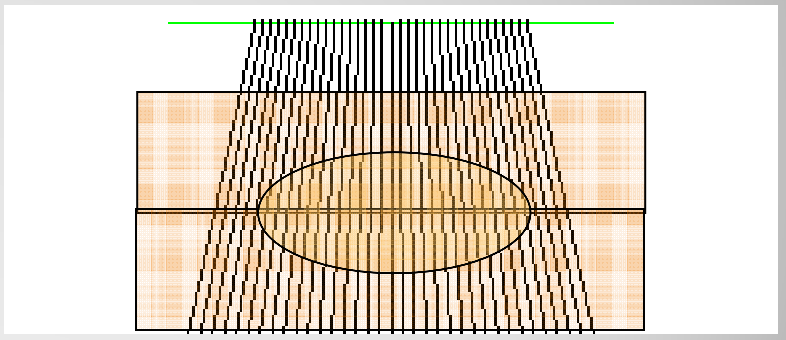




Single Element Vs. Linear Array

Single Element	Linear Array (24 Element)
Images through the center of a weld	Images a cross section of a weld
Combines A-scans to form M-scans	Combines A-scans to form B-scans and M-scans





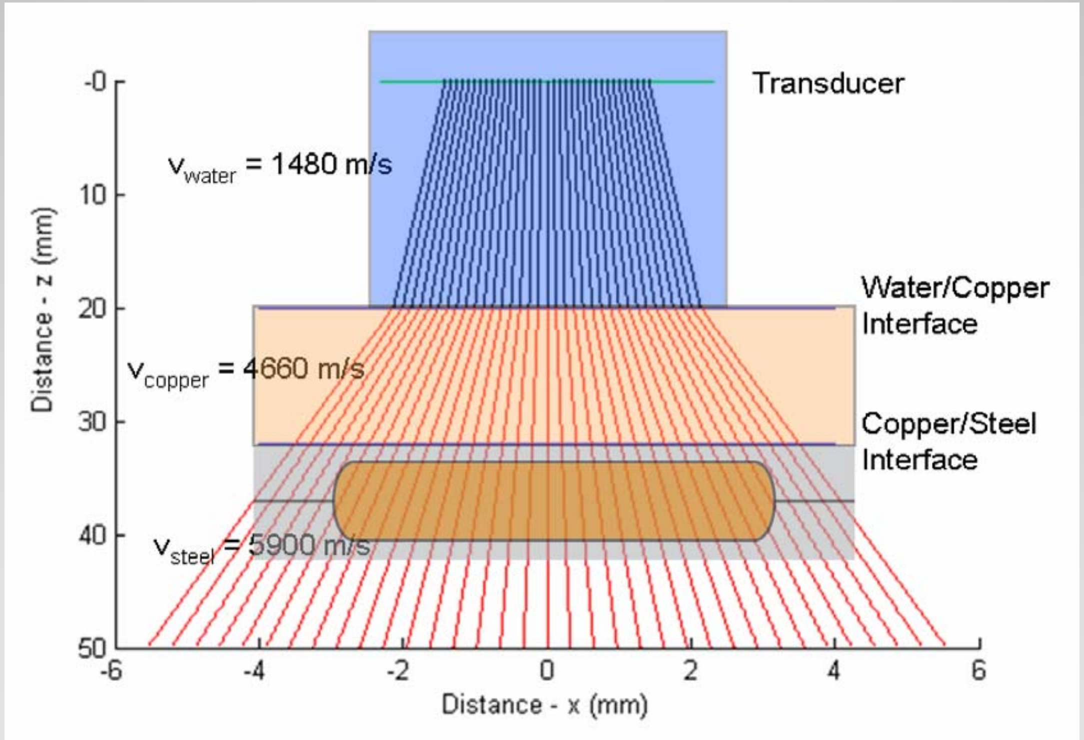
Linear Array Tech Specifications

- 10 MHz center frequency
- 24 Elements
- 0.15 mm element size (0.2 mm pitch)
- 0.05 mm inter-element spacing
- 4 mm elevation (width of elements)
- Key Design Specifications:
  - Select largest aperture possible based on the inner diameter of the welding electrode
  - Minimized the element size to allow for wider beam steering angles (limited by transducer manufacturing process)
  - Select a frequency based on the element size that will still allow steering at the angles required; higher frequencies improve axial resolution but also have greater attenuation
  - Maximize elevation to increase the power of individual elements

Beam Steering

Diffraction of Sound

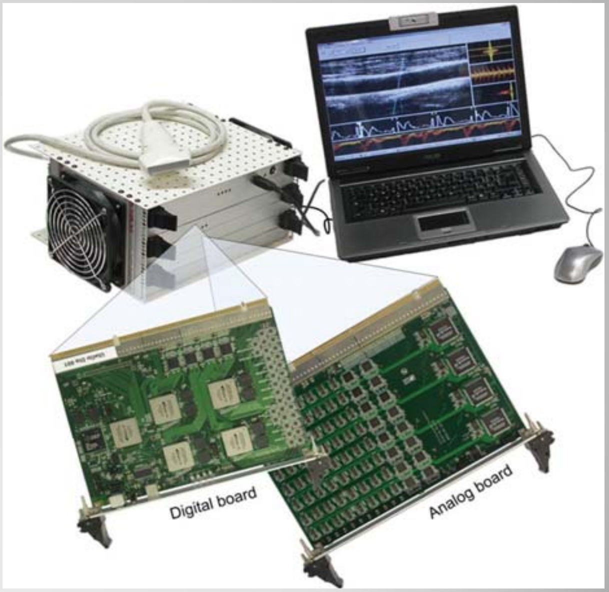
- Sound waves refract when entering a medium with a different speed of sound (Snell's Law)
- Assumed the refraction from copper to steel to be negligible due to thin steel plates and a similar speed of sound



ULA-OP Specifications

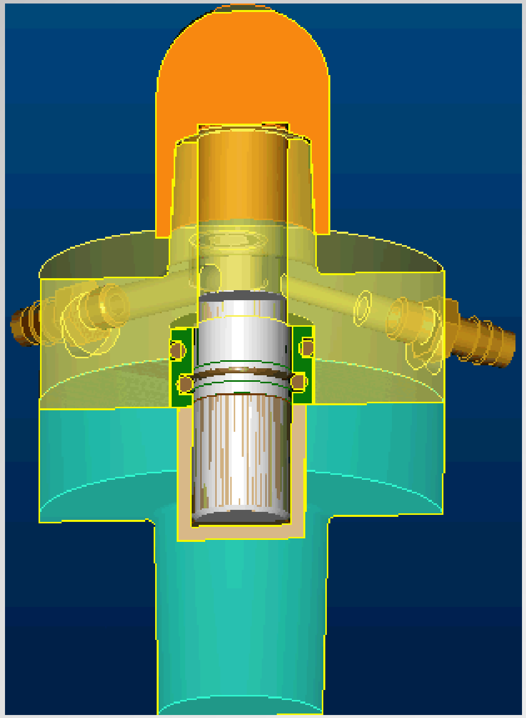
- **Ultrasound Advanced Open Platform developed at the University of Florence**
- **Collaboration between University of Windsor and University of Florence to use the ULA-OP in the phased array welding system**

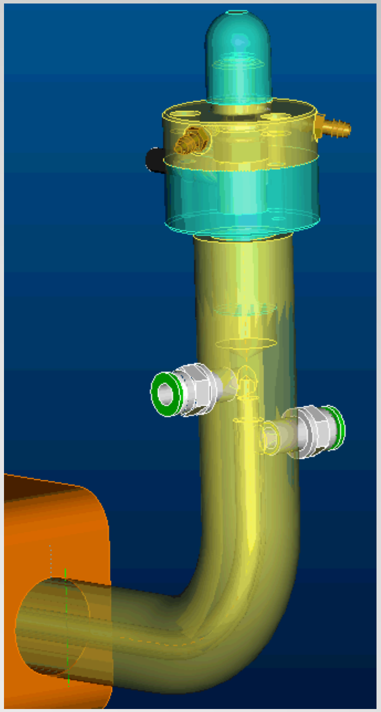
General features	➢ Open platform ➢ 64 independent TX/RX channels ➢ Power consumption < 90W
Transmitter	➢ 64 square wave pulsers ➢ Max output voltage: 150 Vpp ➢ Frequency: 1 to 16 MHz
Receiver	➢ Input noise: 2nV / √Hz ➢ Bandwidth: 1 to 16 MHz ➢ Analog gain: 6-46 dB with programmable TGC ➢ 12 bit @ 50 MSPS ADCs
Beam-former	➢ Programmable apodization and delays (dynamic focusing)
Processing modules	➢ Coherent demodulation, band-pass filtering, decimation, B-mode, multigate spectral Doppler, vector Doppler, custom modules
Storage capabilities	➢ Up to 1 GB for RF data (pre or post beam- formed) ➢ Up to 512 MB for baseband data ➢ Fast data streaming toward high capacity storage units (HD)



Transducer Housing Design

- Water lines were tapped through the electrode instead of the cap
- Transducer housing sits inside the bent adapter
- Sleeve was a two-piece with o-rings to ensure a snug fit

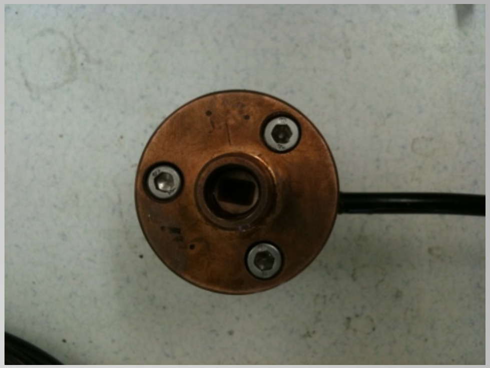




Implementation

Bent Adapter

Housing



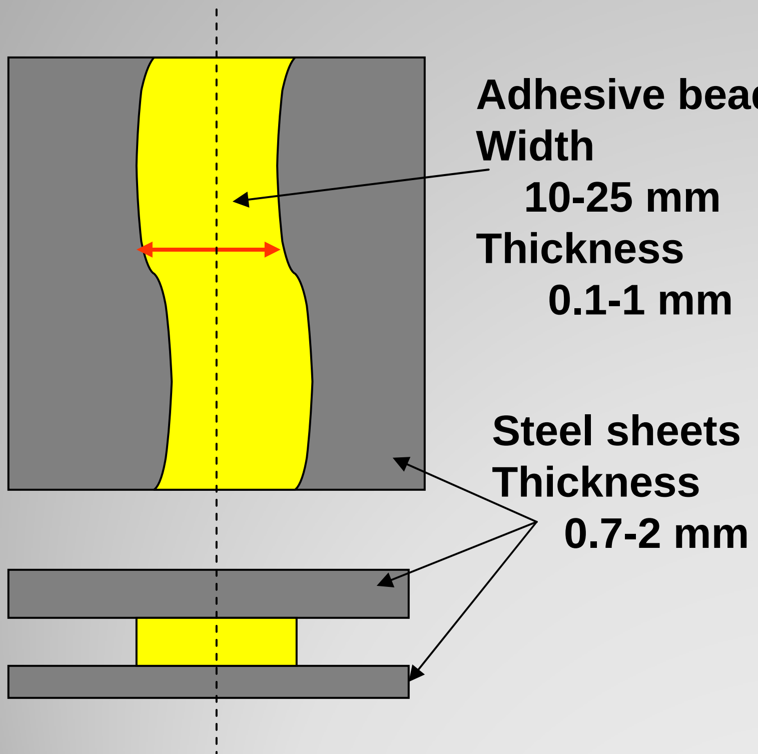
Mounted Transducer

Inspection of adhesive bonding

NDT problem:

•evaluation of the placement and width of adhesive beads

•detection skips and void-like disbonds



Typical automotive adhesive joint

Ultrasonic challenge:

•Large acoustic impedance mismatch between the metal and adhesive;

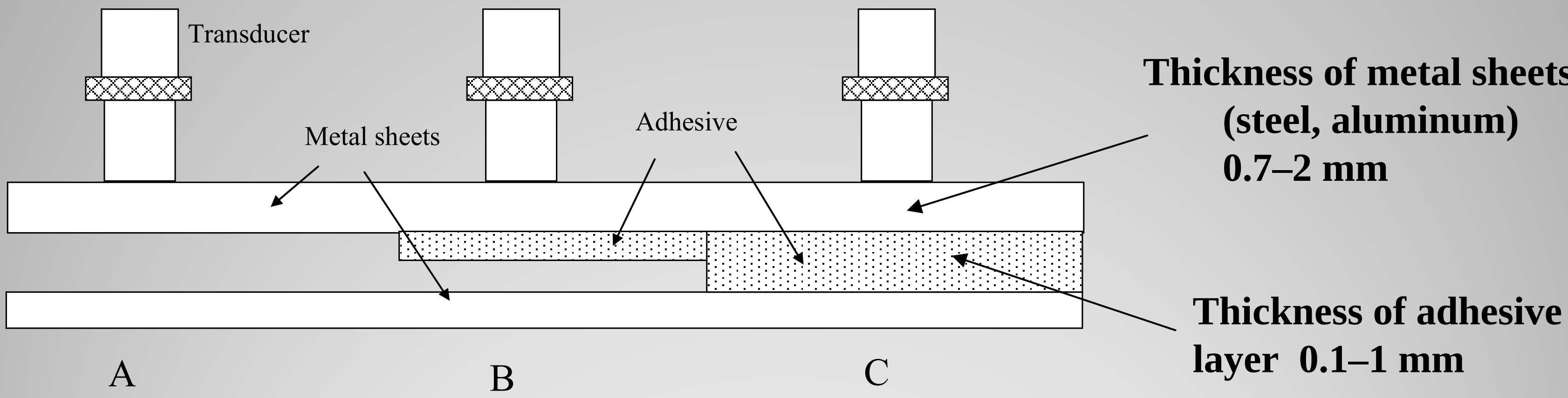
•Thin metal sheets ;

•Uncertainty in the thicknesses of adhesive layer;

•Single–sided access to the joint;

•Small width of the joint (lateral resolution about 1mm is necessary)

The pulse–echo imaging technique of adhesive joints



Types of defects:

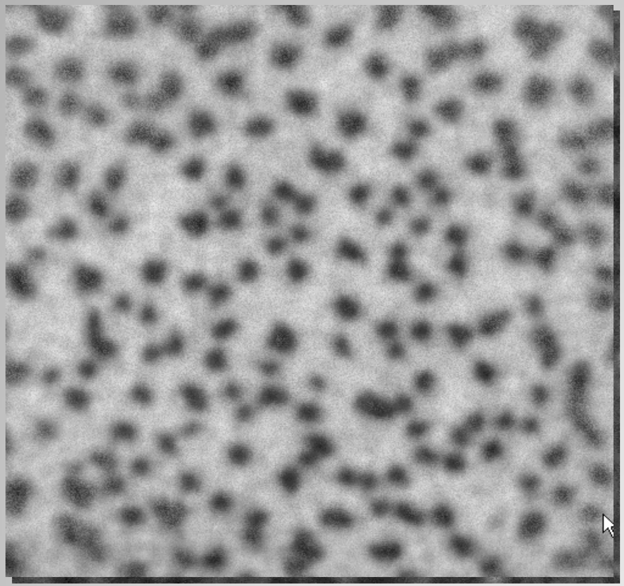
A – missing bond at the first interface

B – missing bond at the second interface

C – good joint

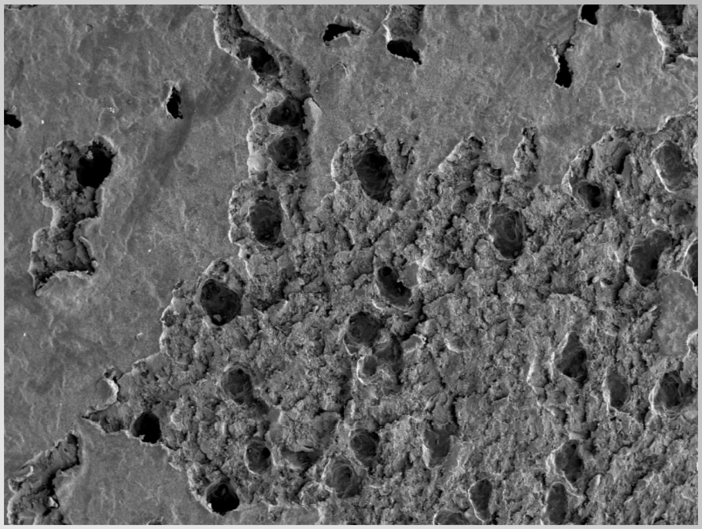
SAM Evaluation of metal-metal Adhesive Bond Joints

2nd interface



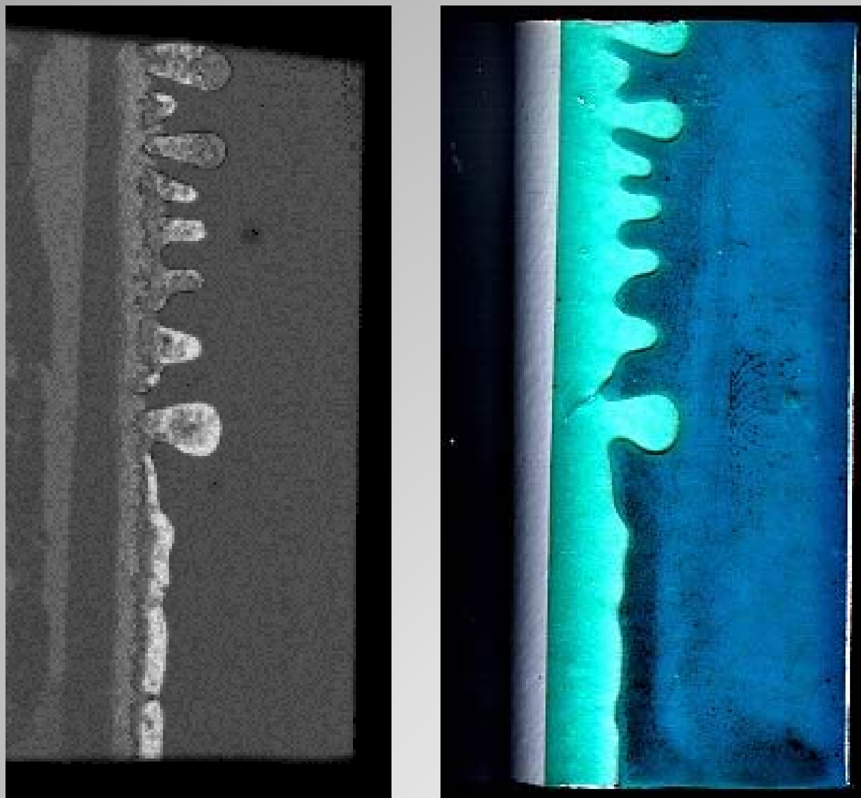
Porosity inside epoxy adhesive due to water adsorption. C-scans of the metal-epoxy-metal sample, 1x1cm area. Average pore size is 0.2mm.

Structure of adhesive layer



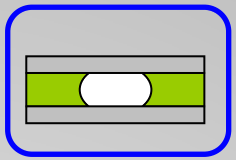
The electron scanning microscope image of the same sample of adhesive.
0.5 x 0.35 cm area. The spherical-shape pores are clearly visible.

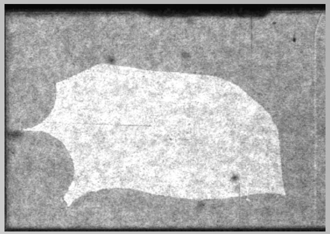
Defects in Adhesive Bond Joints



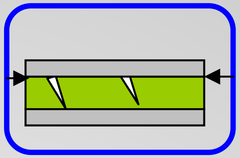
Acoustical image and cross section of adhesive zone (door panel section)

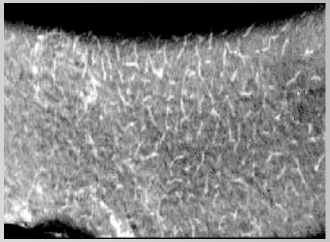
Detectable defects:



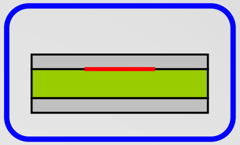


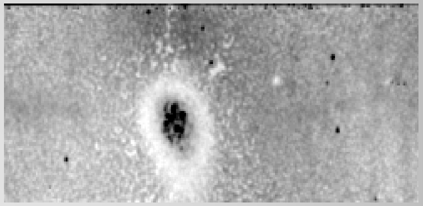
voids



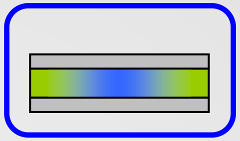


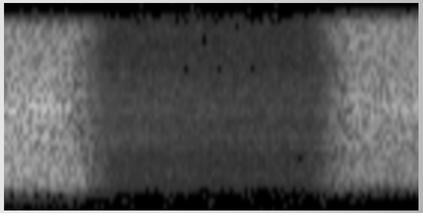
cracks





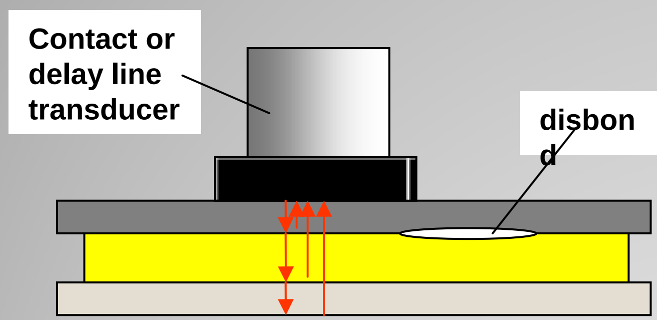
Poor adhesion





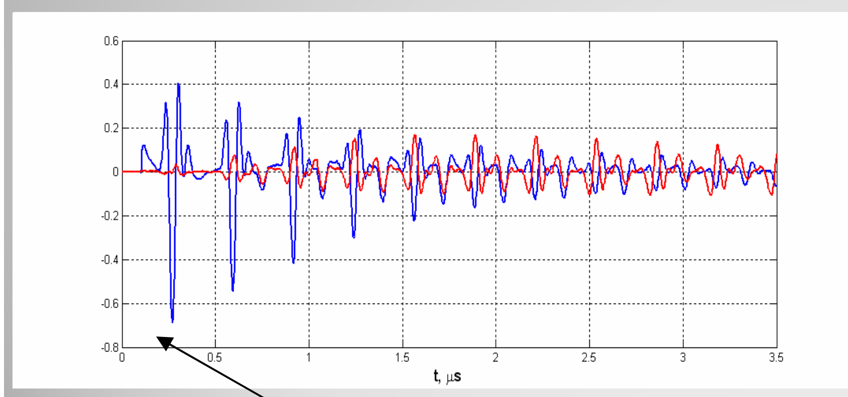
Poor cohesion strength

US Pulse-echo technique



Data processing:

- Spectral analysis (resonance spectroscopy)
- Inverse filtration
- Subtraction of reference waveform



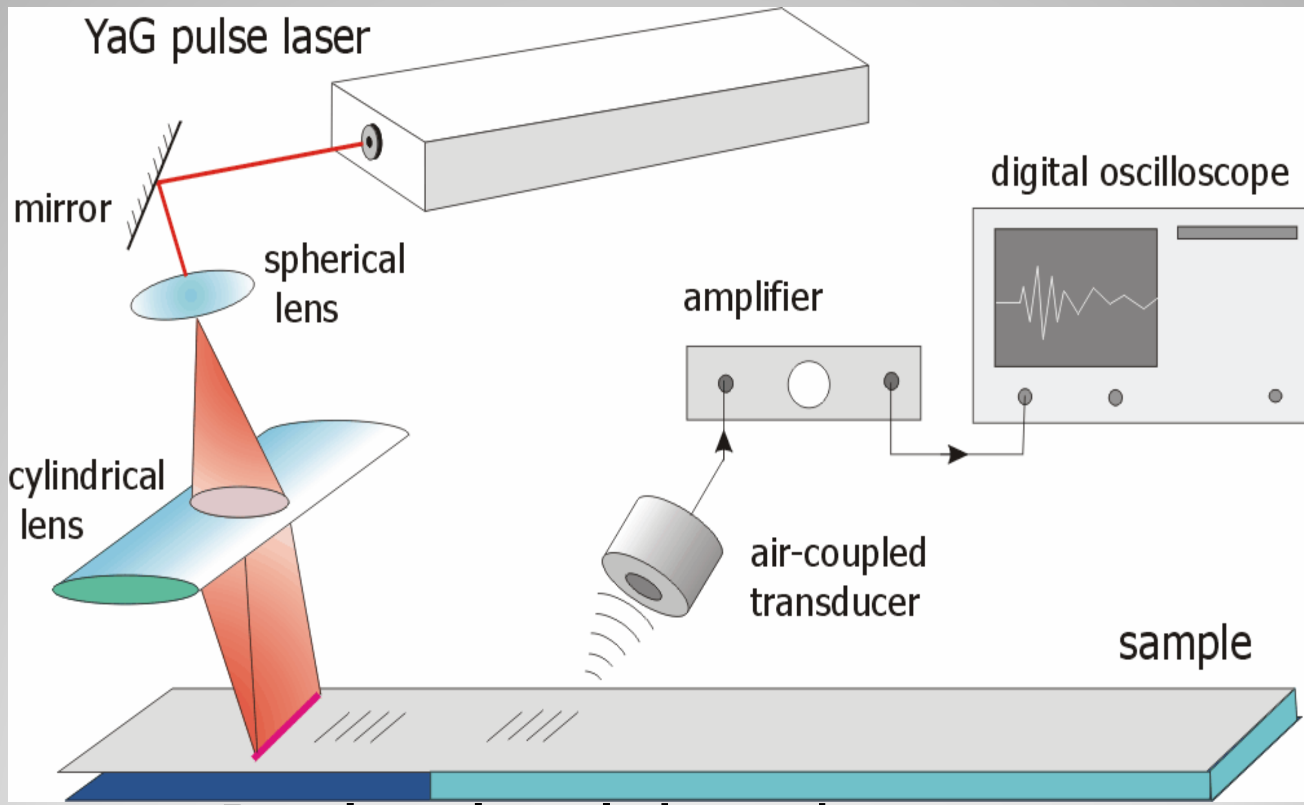
Typical waveform

The results are not robust with respect to

- waveform distortion
- adhesive and metal thickness variation,
- curvature and roughness of surface,
- quality of acoustical contact

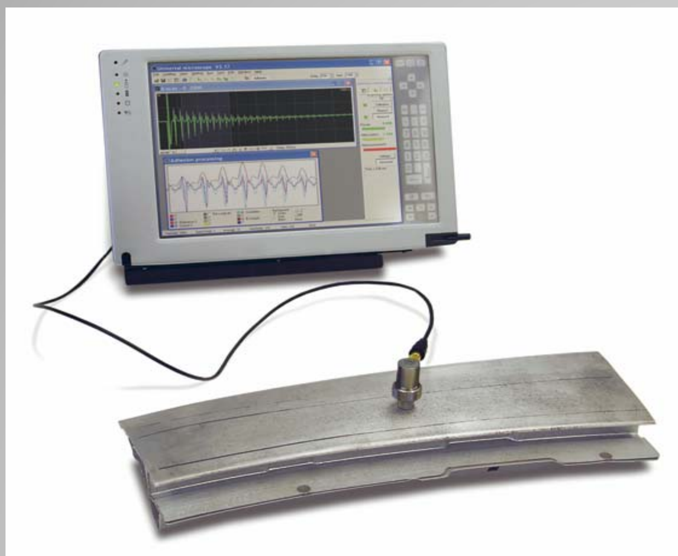
Low lateral resolution

Lamb wave measurement (contact or non-contact)



Poor lateral resolution and sensitivity to thickness variation

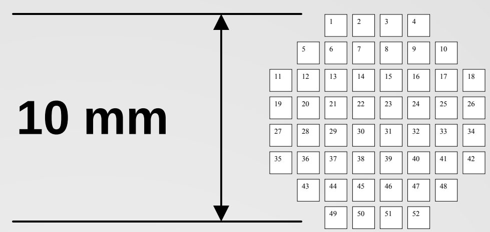
Industrial prototype of the Adhesive bond inspection system (ABIS)



52-element Matrix Array Probe

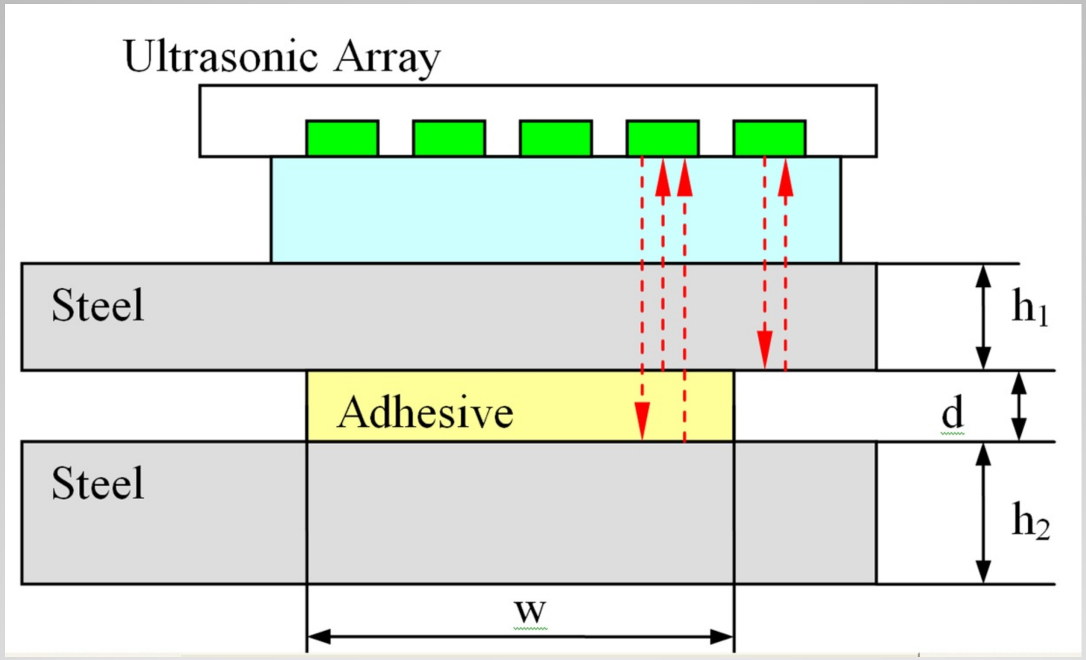
15 MHz central frequency
70 % bandwidth
1.25 mm pitch

52-channel ultrasonic unit (Tessonics Corp., Windsor, On., Canada)



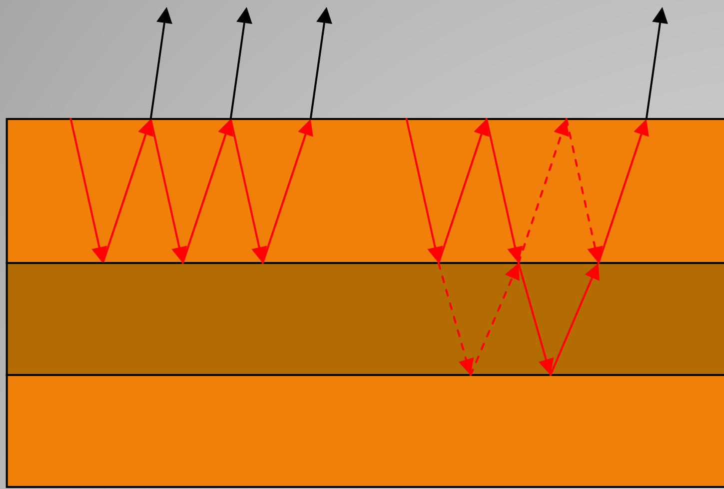
Matrix array layout

Adhesive Bond Inspection System (ABIS)



To achieve sufficient lateral resolution, a matrix array consist of small transducers has been proposed for evaluation of adhesively bonded joints.

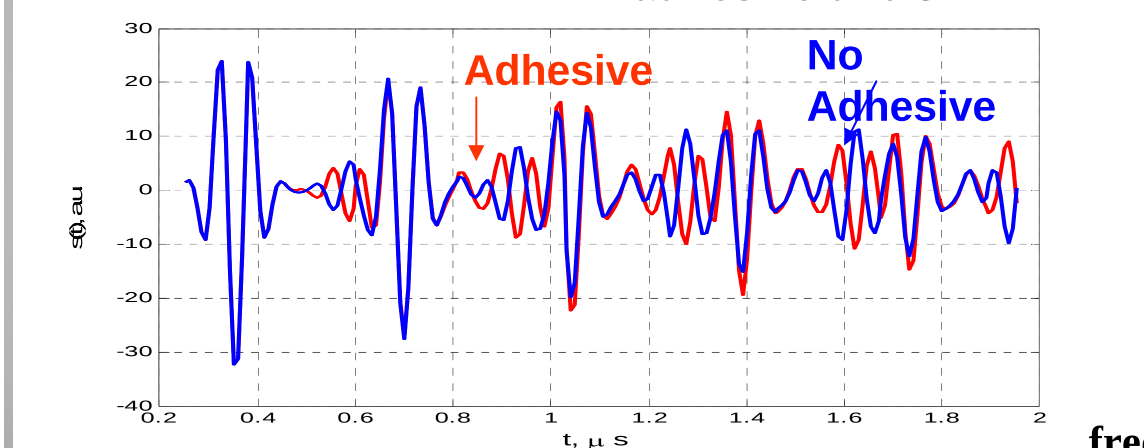
Numerical simulation

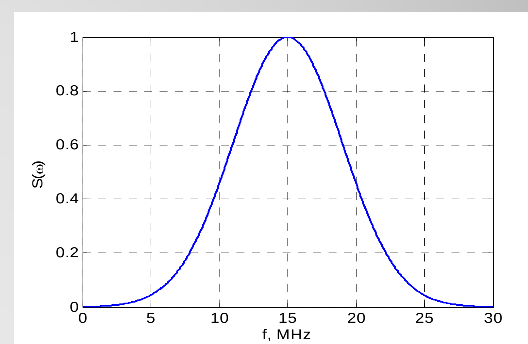


Output waveform can be obtained as inverse Fourier transform:

$$Z_{in}^{(j)} = Z_j \cdot \frac{Z_{in}^{(j-1)} - iZ_j \cdot \tan(k_j d_j)}{Z_j - iZ_{in}^{(j-1)} \cdot \tan(k_j d_j)}$$

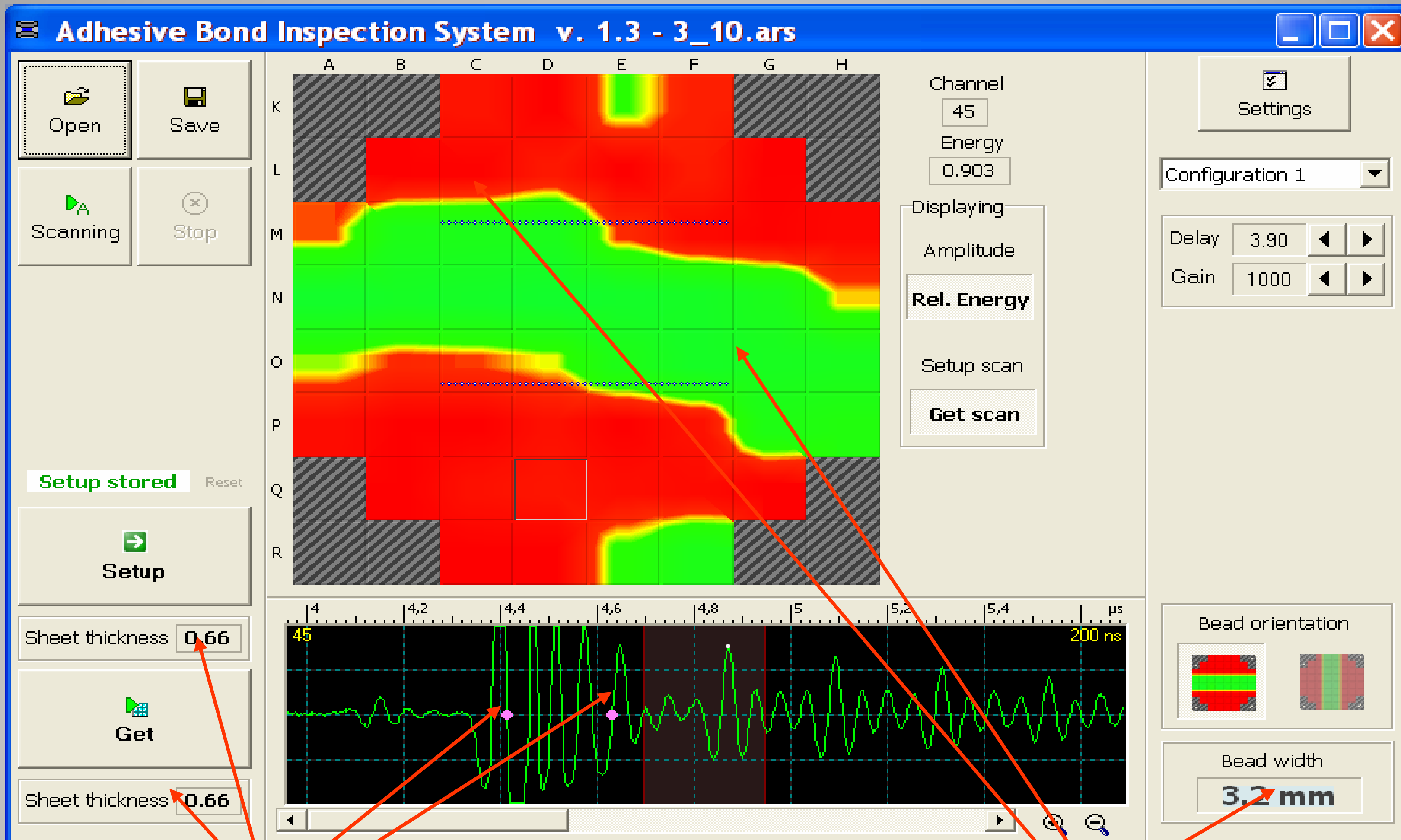
Simulated waveforms. steel h_1=1mm, adhesive d=0.3 mm





frequency response of system $S_{sys}(\omega)$

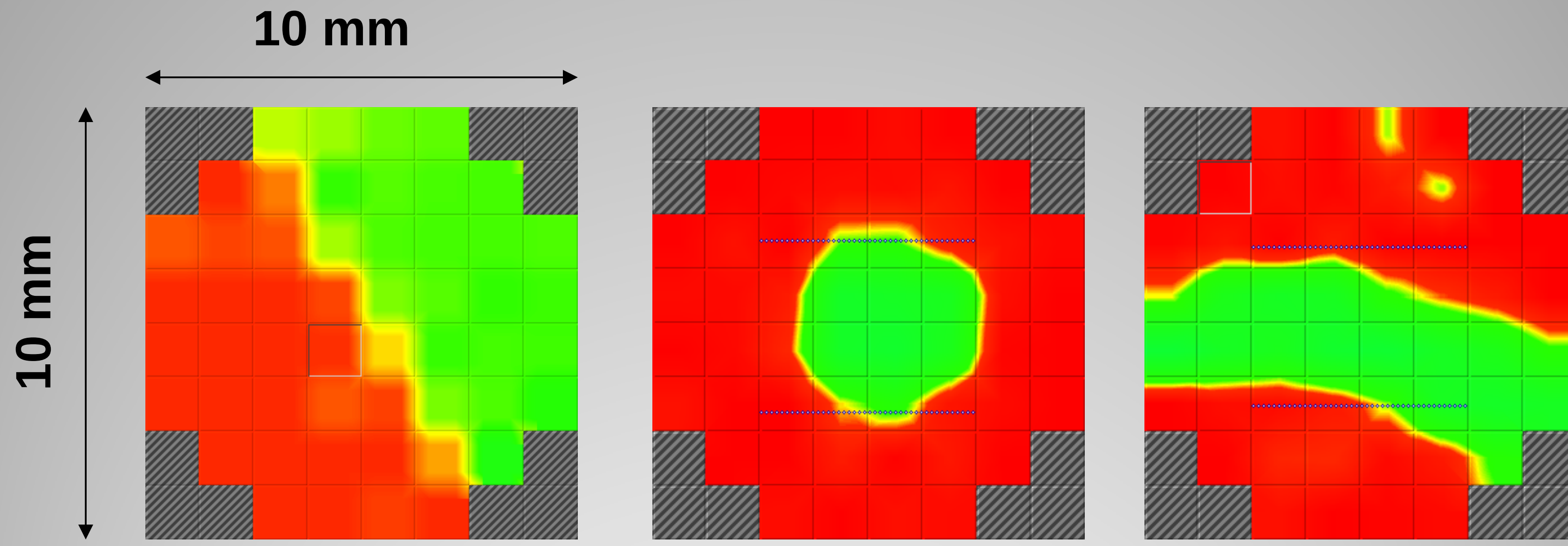
ABIS: Graphical User Interface



Sheet thickness

Bead width

Examples of the ABIS C-scans



Linear boundary "Adhesive / no adhesive"

3.5 mm diameter Adhesive droplet

2.7 mm strip

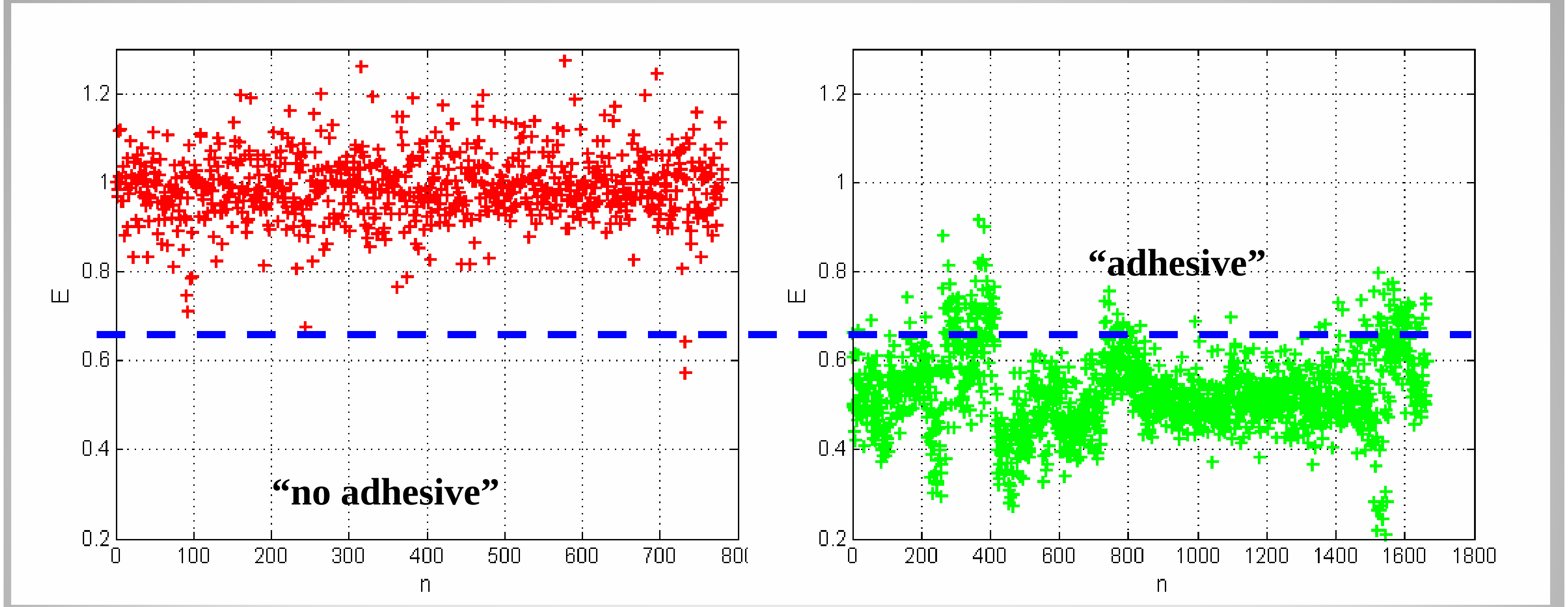
Steel sheet had a thickness of 0.7 mm

Threshold parameters were set as follows: E_1=0.7, E_2=0.8, E_T= 0.75

Reliability and accuracy of measurements

Laboratory trial

The threshold values were determined by statistical analysis of experimental data



The larger variation of the "adhesive" data points compared to the "no adhesive" data set is related to the varied adhesive thickness.