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

Detectable imperfections:
- Insufficient length
- Seam interruption
- Lack of fusion
- Pin hole existence

0.75 mm thick (left) and 1mm thick (both right) steel plate with approximately 3 mm width welds
Portable Hand-Held Imaging Solutions
Multi-Lens System

Data acquisition and PC interface block

PC

MUX
Multilens US Transducer
Multi-Lens System
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
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

Reflected amplitude, mV vs. Depth, mm
Tilt Compensation

Effect of refraction of the beam on a tilted interface

\[ \theta = \arcsin \left( \frac{1.4}{ka} \right) \]

\[ D_{123} = \frac{D_{12} D_{23} e^{-jk_2h}}{1 - R_{21} R_{31} e^{-j2k_2h}} \]

\( D_{ij} \) 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
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

Single element probe built into electrode

Incident wave

Copper Electrode

Steel Plate 1

Molten Nugget

Steel Plate 2

Copper Electrode

A-scan

Amplitude

Arrival time

Current ON

Arrival Time

Welding time
M-scan Formation

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

![Diagram of M-scan Formation with Amplitude, Arrival Time, and Welding time axes.]
Array: Reflection method

Top electrode

Wave

Welded sheets

Bottom electrode
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

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**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**

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**Single Element Transducer**

**Linear Array Transducer**
**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
**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

**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

Thickness of metal sheets (steel, aluminum)
0.7–2 mm

Thickness of adhesive layer
0.1–1 mm
SAM Evaluation of metal-metal Adhesive Bond Joints

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

Detectable defects:

- voids
- cracks
- Poor adhesion
- Poor cohesion strength

Acoustical image and cross section of adhesive zone (door panel section)
US Pulse-echo technique

Data processing:

- Spectral analysis (resonance spectroscopy)
- Inverse filtration
- Subtraction of reference 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
To achieve sufficient lateral resolution, a matrix array consisting of small transducers has been proposed for evaluation of adhesively bonded joints.
Numerical simulation

Output waveform can be obtained as inverse Fourier transform:

\[
Z_{in}^{(j)} = Z_j \cdot \frac{Z_{in}^{(j-1)} - iZ_j \cdot \tan(k_jd_j)}{Z_j - iZ_{in}^{(j-1)} \cdot \tan(k_jd_j)}
\]

Simulated waveforms. steel \(h_1=1\text{mm}\), adhesive \(d=0.3\text{ mm}\)

frequency response of system \(S_{sys}(\omega)\)
ABIS: Graphical User Interface

Sheet thickness

Bead width
Examples of the ABIS C-scans

10 mm

10 mm

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.