Quantitative Simulation of Ultrasonic and EMAT Arrays Using FEM and FDTD

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Contents

- Introduction
- Ultrasonic NDT
- Electromagnetic-acoustic (EMAT) NDT
- Conclusion and future work
Introduction

Ultrasonic testing (UT) applications

- Thickness Measurement
- Flaw Evaluation
- Material Characterization

Motivations

- Use ultrasonic waves to detect steel welding
- EMAT is a relatively new NDT technique
- Comparison and combination
Ultrasonic NDT

- Piezoelectric transducer
  - electrical energy
  - mechanical energy
  - acoustic energy
Ultraasonic NDT

- Ultrasonic testing principle

Diagram showing the principle of ultrasonic testing with a transducer, crack, initial pulse, and back surface signal.
Ultrasonic NDT

➤ One element---multiple elements--phased array

Phased array technique: with firing elements at different time, the wavefront can be controlled to steer at an arbitrary angle or focus at a specific point.
Beam steering simulation geometry
Beam steering behaviour

steering angle = 0 (degree)

steering angle = 30 (degree)

steering angle = 60 (degree)

steering angle = 90 (degree)
Beam focusing simulation geometry
Beam focusing behaviour

The wavefront is concentrated on the focal point (500,500).
Radiation pattern

- Conventional radiation pattern

Each point on simulation geometry has a time series signal, and the max amplitude at each point, indicating the arrival time of the signal, forms the radiation pattern.

- Hilbert transform

Hilbert transform makes a 90 degree phase shift from the real signal $f(t)$, and in turn forms the analytical signal $z(t)$.

$$z(t) = f(t) + j(f(t))$$

$$envelop = \sqrt{(f(t))^2 + (f(t))'}$$
Radiation pattern

Radiation pattern defines the distribution of the acoustic energy and is used for analyzing the beam features.

• Beam directivity

At a radial length from the centre of the array, the field distribution (along the red circle). The steering angle calculated is $27.5^0$.

• Field distribution

The velocity distribution along the steering angle (green line). The calculated focal length is 564 space steps.
Beam features

- Beam directivity
  
  At the steering angle $27.5^\circ$, the radiation pattern shows a good directivity and has the largest magnitude.

- Velocity distribution
  
  The maximum magnitude occurs at the focal distance slightly small than 564 space step due to the effect of distraction.
Scattering simulation geometry

- Focus at the scatter
Scattering behaviour

- Waves propagation with the PML boundary
The amplitude of the 1\textsuperscript{st} receiver is slightly smaller than that of the 8\textsuperscript{th} receiver due to the attenuation of ultrasound waves.

Go to experiments part.
Experiments of ultrasonic NDT

MicroPulse 5PA

Transducer: 64 elements
Working frequency: 2.25M Hz
Sampling frequency: 25M Hz
Experiments of ultrasonic NDT

- Testing sample
Image rendering
Conclusion of ultrasonic NDT

➢ Advantages

• The depth of penetration for flaw detection or measurement is superior to other NDT methods.
• high electroacoustic efficiency
• low acoustic impedance and mechanical flexibility

➢ Disadvantages

• contact is needed, always by means of couplant.

A relatively new technique EMAT, offers an attractive feature due to its non-contact nature.

Let's go to EMAT part.
An EMAT sensor consists basically of a coil carrying an alternating current, a permanent magnet providing a large static magnetic field, and the test piece.
**EMAT mechanisms**

- Lorentz force mechanism (for conductive metallic materials)

**Transmitting process**: Lorentz force $F$ generates ultrasonic waves.

$$ F = J_e \times B_s $$

**Receiving process**: the inverse process of transmitting: moving atoms and electrons experiencing Lorentz force generates dynamic magnetic field which is detected by the receiving EMAT transducer.
EMAT non-contact nature

• Piezoelectric transducer

Piezoelectric transducer generates ultrasonic waves in the transducer, and couplant is needed for mechanical waves propagation to match the impedance.

• EMAT

EMAT generates ultrasonic waves in the testing object instead of the transducer. So contact is not necessary for EMAT. However, the efficiency of EMAT is poor compared to piezoelectric transducer.
EMAT simulation

Electromagnetic simulation (Ansoft Maxwell)

Objectives: Obtain the Lorentz force for a given coil and magnet configuration

Ultrasonic simulation (SimSonic)

Objectives: Model the velocity fields of ultrasonic waves.
The distribution of B (left) and J (right)

The maximum magnetic field occurs near the edges of the permanent magnet, and the induced eddy currents are mainly distributed along the meander coil.
The distribution of Lorentz force density

Assuming the surface of the steel plate contains 301*301 space steps, the $y$ component of Lorentz force density is a 301*301 matrix as well. By averaging the value of every row in the matrix, the 3-D model is simplified to a 2-D model.
The radiation pattern of Rayleigh waves

Based on constructive interference, a Rayleigh wave is produced along the surface of the testing sample.
Conclusion and future work

➤ Conclusion

• Ultrasonic simulation (FDTD)
  1. Steering, focusing, and scattering behaviours.
  2. Radiation pattern and beam features.
• EMAT simulation (FDTD+FEM)
  1. The distribution of B, J and Lorentz stress (FEM).
  2. Lorentz stress is used as the source excitation to generate Rayleigh waves (FDTD).
  3. The radiation pattern of the Rayleigh waves and beam features.

➤ Future work

• Simulation improvement.
• Mainly focus on EMAT experiments.
Experiments of EMAT NDT
THANK YOU

QUESTIONS?