EXPERIMENTAL VALIDATION OF AN 8 ELEMENT EMAT PHASED ARRAY PROBE FOR LONGITUDINAL WAVE GENERATION

QNDE 2014
Florian Le Bourdais and Benoît Marchand
CEA LIST, Centre de Saclay F-91191 Gif-sur-Yvette, France
1. Context: inspection needs within the ASTRID Generation 4 project
2. Parametric study on optimal magnet position using simulation tools
3. Experimental setup of the phased array probe and signals on calibration block
4. Conclusions and perspectives of the project
1. CONTEXT: INSPECTION NEEDS WITHIN THE ASTRID PROJECT
The French nuclear program currently undertakes the Advanced Sodium Technical Reactor for Industrial Demonstration (ASTRID) project

- In-service inspection methods for improved safety have been part of the design from the very start
- Planned inspection types include inspection from within the main vessel, with a dedicated under-sodium probe

**Probe operating conditions during inspection shutdown**

- Probe immersed into liquid sodium at 200°C
- Slow sodium flow
- Radiation conditions: up to 300 Gy/h
- Short service time: 30 days maximum

**Inspection needs**

- Object detection
- Distance measurements and surface metrology
- Imaging for exploration purposes
- Non-destructive testing of components

**Therefore, ongoing work to enhance existing piezoelectric probes and develop new techniques**

- In particular, development of EMAT probes for liquid sodium since 2008 at CEA LIST
2. PARAMETRIC STUDY ON OPTIMAL MAGNET POSITION USING SIMULATION TOOLS
PREVIOUS WORK (2008 - TODAY)

- Development of single-element probes for longitudinal wave generation
- Repeated liquid sodium testing at dedicated CEA facilities
- Modeling of Lorentz force EMAT fields and implementation within the CIVA software
- Development of first phased array probe in 2013 (and irradiation tests)
- Development of second phased array probe in 2014 → topic of today’s talk

\[ \mathbf{F}_{\text{Lorentz}} = \mathbf{J} \times \mathbf{B} \]
CUMRRENTLY DEVELOPED PHASED ARRAY PROBE

- Linear phased array pattern (8 elements)
- Coils etched on 4 layers of Kapton
- Use of LEMO connectors for multi-channel electrical input
- The magnetic system is to be positioned manually on the coils
  - Several type of magnets are available in the laboratory but we focus on one particular type of ferrite magnet assembly
- The goal of this study is to find the optimal magnetic system disposition for the existing coils and testing this configuration
THE PHYSICS OF MAGNETS FOR EMAT PROBES

• Let’s consider the distance between the magnets and the lift-off relative to the coils as parameters

• Small magnet distance and lift-off: high magnetic field amplitude but not very horizontal field lines

• High magnet distance and lift-off: low magnetic field amplitude but very horizontal field lines

• The optimal configuration is ultimately a tradeoff between amplitude and horizontality of $B$
PARAMETRIC STUDY GOAL

- **Probe parameters: lift-off and distance between two magnets**
  - First parameter: magnet separation distance
  - Second parameter: lift-off relative to the coils of the EMAT probe

- **By choosing sensible input parameter values, the parameter space is discretized and evaluated (in practice: evaluation on a grid)**
The physical principle responsible for generating an ultrasound wave is the Lorentz force due to the static magnets and the eddy currents.

Our simulation model computes the Lorentz force integrated over the spatial $z$ component:

$$\sigma = \int_{z=-\infty}^{z=0} J \times B \, dz$$

In the example below, the area of interest exhibits large amplitude differences which has a detrimental effect on ultrasound generation (focusing, sweeping) as each element emits a wave of a different amplitude, as well as secondary sources.

To evaluate the quality of a given configuration, we define several numerical criteria based on the surface Lorentz distribution.
CRITERIA FOR EVALUATING THE OPTIMAL MAGNET POSITION

- We focus on the $\sigma_{zz}$ contribution alone
- Maximum amplitude of the Lorentz force along $z$ direction in the effective area $c_1$ (a)
- Maximum amplitude of the Lorentz force along $z$ direction outside the effective area $c_2$ (b)
- Ratio of maximum to minimum amplitude of Lorentz force along $z$ direction over the 8 phased array elements in dB $c_3$ (c)
Example for maximum amplitude of Lorentz force along $z$ direction in the effective area

- Refinement of parameter space to magnet distance $\in [15; 30]$
- Extraction of meta-criterion
INTRODUCTION OF META-CRITERION ON REFINED CONFIGURATION

- It is difficult to choose from 3 scalar values simultaneously.
- To ease the choice of the optimal configuration, a meta criterion is defined.
  \[ c_{\text{meta}} = \sum_{i=1}^{3} \left( \frac{c_i}{c_i^0} \right)^{w_i} \]
  where \( w_i \) are power law weights, \( c_i \) are the previously introduced criteria and \( c_i^0 \) is a dimensional normalizing constant.
- In our case we use the following normalizations:
  - \( c_1^0 \) = maximal observed value of amplitude over entire parameter space grid
  - \( c_2^0 \) = maximal observed value of amplitude over entire parameter space grid
  - \( c_3^0 \) = 6 dB
- Different sets of parameters give different iso-surfaces (90%, 70%, 50%, 30%).

![meta indicator (max: 1.25, returns: -1.0, coil ratio: -0.5)](image1)

![meta indicator (max: 1.25, returns: -0.5, coil ratio: -0.5)](image2)

![meta indicator (max: 3.0, returns: -2.25, coil ratio: -1.75)](image3)
OPTIMAL CONFIGURATION

- Final choice of weights is \((\text{maximum amplitude, amplitude of returns, amplitude ratio for coils}) = (1.5, -1.75, -1.75)\)
- Configurations are restricted to less than 6 dB coil differences and returns less than 45 % of maximum amplitude

indicator_max = 147.39
indicator_returns = 61.86
indicator_max_coil = 0.59
3. EXPERIMENTAL SETUP OF THE PHASED ARRAY PROBE AND SIGNALS ON CALIBRATION BLOCK
TESTING CONFIGURATION: BACKWALL ECHO

- A specially designed electronic pulser is used to power the EMAT probe
- Driving signal is a 300 V single negative pulse at 2 MHz
- The received signal is averaged 16 times
- An A-scan showing the backwall echo of our aluminium calibration block is obtained
The beam steering capabilities of the probe were demonstrated on the backwall.

Delay laws were calculated according to the following formula:

- Pitch of the phased array: \( p = 1.5 \text{ mm} \)
- Transmit delay of element \( i \): \( \tau_i^E = i \frac{p \sin \theta}{c_{Alu}} \)
- Receive delay of element \( i \): \( \tau_i^R = -i \frac{p \sin \theta}{c_{Alu}} \)
- Total delay for couple \( (i, j) \) is \( \tau(i, j) = \tau_i^E + \tau_j^E \)

Resulting image
4. CONCLUSIONS AND PERSPECTIVES OF THE PROJECT
CONCLUSIONS AND PERSPECTIVES

• An EMAT phased array probe was designed and manufactured
• The magnetic assembly part of the probe was successfully optimized according to a multi-objective criterion with the help of a simulation model
• The derived magnetic assembly configuration was tested experimentally
• The probe was successfully used to generate A-scans and B-scans on an aluminium block

• Perspectives
  • Laboratory testing on block with drill holes
  • Liquid sodium testing
  • 24 element EMAT system will be received at CEA LIST at the end of the year: improved probe design
THANK YOU FOR LISTENING! QUESTIONS?