Finite element modeling of pulsed spiral coil Electromagnetic Acoustic Transducer (EMAT) for testing of plate

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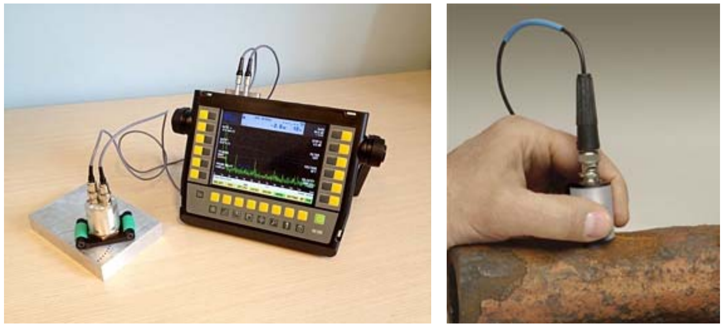
COMSOL
CONFERENCE
BANGALORE 2013

Overview

- Introduction of EMAT
- Governing equations
- Electromagnetic modeling
- Elastodynamic modeling
- Generation of plate wave
- Defect detection using plate wave
- Summary and conclusions
- References

Electromagnetic Acoustic Transducer (EMAT)

EMAT is a transducer for non-contact sound generation and reception using electromagnetic mechanisms.



- Electrically conducting materials
- All types of sound wave modes
- High speed scanning
- No couplant

Applications

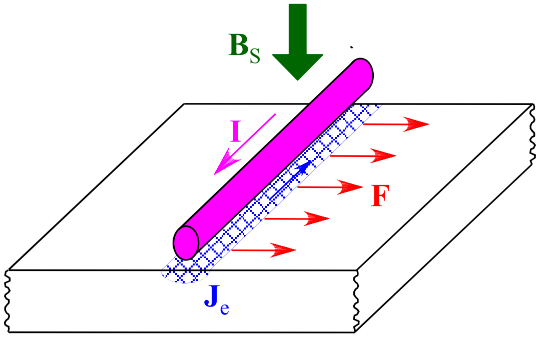
- Weld Inspection
- Thickness measurement
- Guided wave Inspection
- Material Characterization
- Pipeline in-service Inspection
- High Temperature Inspection

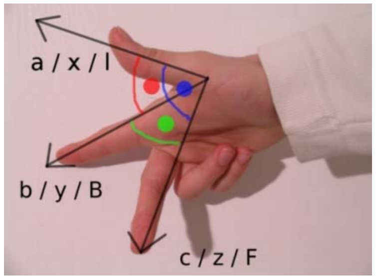
Physical Principle of EMAT

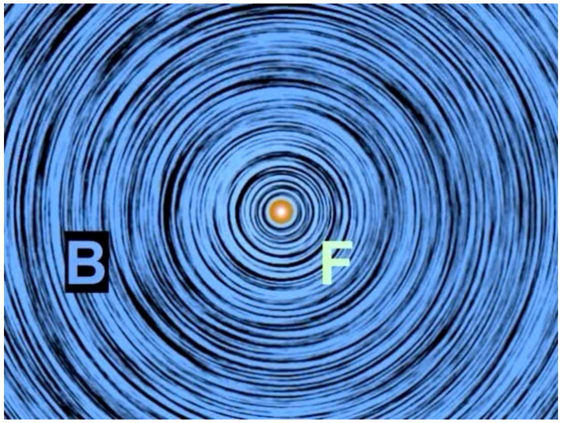
Lorentz force $\vec{F}_L(Z) = \vec{j}_e(X) \mathrm{\ x\ } \vec{B}_S(Y)$

Where $\vec{j}_e$ – induced current density (amp/m^2)

$\vec{B}_S$ – applied static magnetic field (Tesla)







http://ocw.mit.edu/OcwWeb/Physics/8-02Electricity-and-MagnetismSpring2002/DownloadthisCourse/index.htm

Objective and Scope

The prime objective of the present work is to develop a finite element model of pulsed spiral coil EMAT transmitter for generating plate waves.

The scope of the work is

- to design a 2D electromagnetic transient model for the Lorentz force density calculation. (AC/DC quasi-static magnetic mode)
- to simulate the ultrasonic plate waves by utilizing the Lorentz body forces as sources of wave propagation. (Structural mechanics plain strain mode)
- to analyze and compare the plate wave with DISPERSION curves.

Governing equations

Electromagnetic field Equations

The transient electromagnetic field for a transmitting EMAT may be stated in terms of the Magnetic vector potential (MVP) and the Source current density (SCD)

$$\frac{1}{\mu}\nabla^2 A_z + \sigma\frac{\partial A_z}{\partial t} - + \frac{\sigma}{S_k}\frac{\partial}{\partial t}\iint A_z ds = \frac{i_k(t)}{S_k} = j_{sk}$$

Where μ, σ, A_Z i_k,S_k and j_{sk} are the permeability, conductivity, magnetic vector potential (MVP), total current, cross-sectional area of the sources and source current density (SCD) of the k_{th} source conductor, respectively.

R. Jafari-Shapoorabadia and A. Konradb," The governing electrodynamic equations of electromagnetic acoustic transducers," *Journal of Applied Physics* 97, 10E102 (2005).

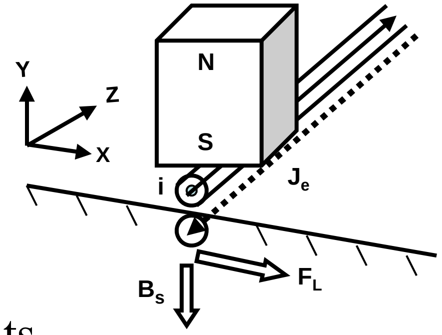
Governing equations

Acoustic field Equations

The Lorentz force causes the vibration of the atomic structure of the material which leads to the generation of acoustic wave inside the conducting materials.

$$F_L = j_{sk} \times B_0$$

The acoustic field equation can be stated in terms of the particle displacement vector υ and the Lorentz force as

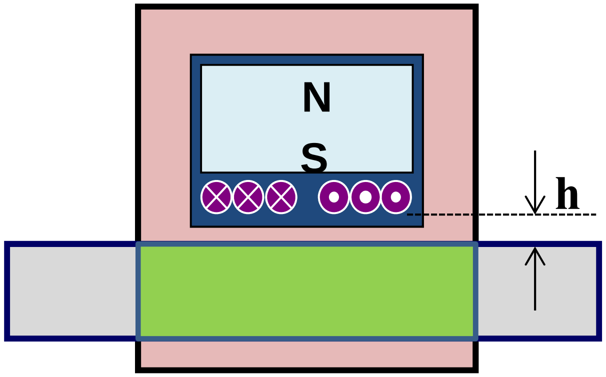


$$\mu\nabla\times\nabla\times\upsilon-(\lambda+2\mu)\nabla\nabla\cdot\upsilon+\rho\frac{\partial^2\upsilon}{\partial t^2}=F_L$$

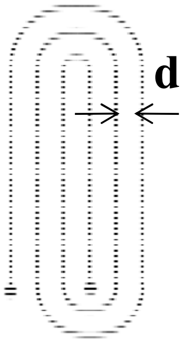
Where ρ is mass volume density and λ and μ are Lame constants.

Dhayalan, R. and K. Balasubramaniam, "A two stage finite element model for a Meander coil Electromagnetic Acoustic Transducer Transmitter", *Nondestructive testing and Evaluation*, Vol. 26(2), pp. 101-118, 2011.

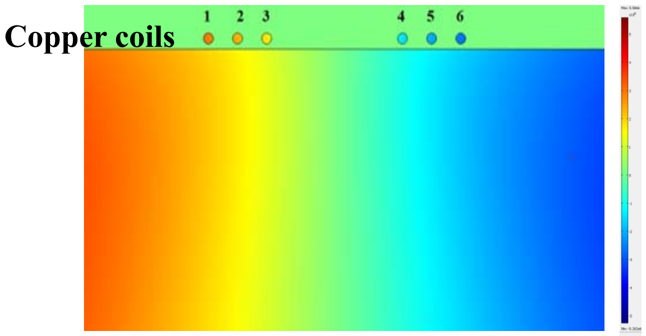
Electromagnetic model - Spiral coil EMAT



Spiral coil



EM model



🟥 Electromagnetic model

⬜ Elastodynamic model

🟩 Multiphysics model

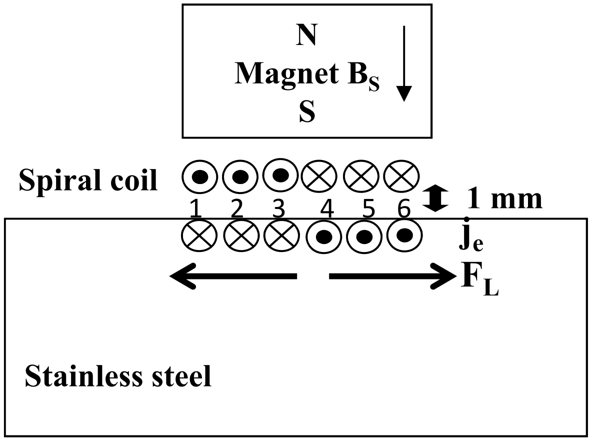
Coil diameter (a) - 1 mm

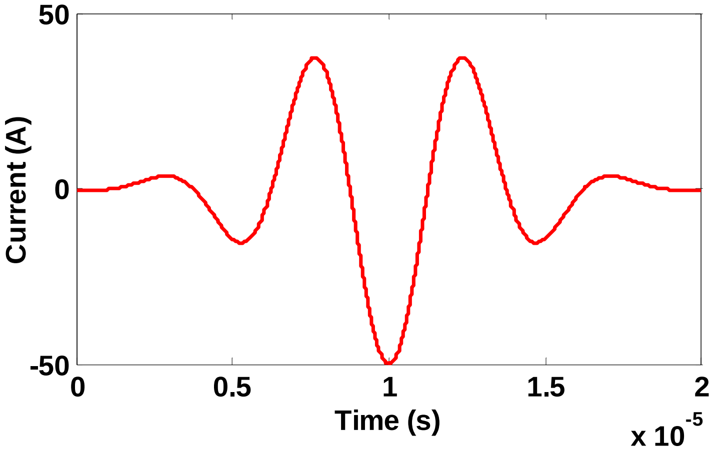
Coil spacing (d) - 3 mm

Coil Lift-off (h) - 1 mm

Flux density (B) - 0.3 Tesla

Input Excitation current





The Input current i(t) for the EMAT coil is,

$$i(t) = \beta e^{-\alpha(t-\tau)^2} \cos\left(2\pi f_c (t-\tau) + \phi\right)$$

Where, β – Amplitude – 50 Amp

α – Bandwidth factor – 5e-10

τ – Arrival time – 10 μsec

f_c – Central frequency – 200 kHz

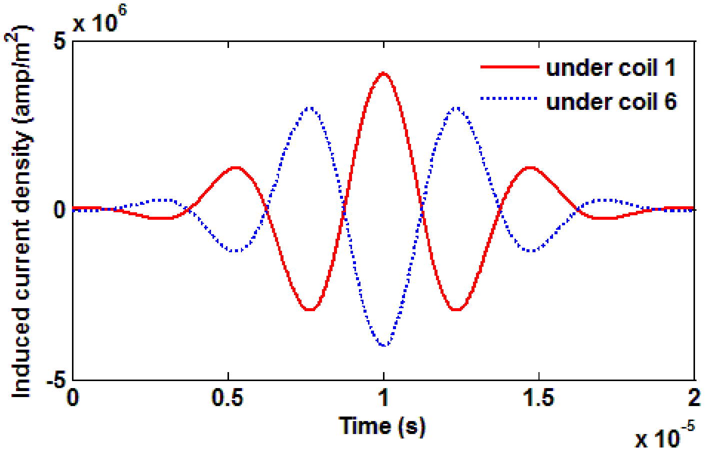
Lorentz force density Calculation

Induced Current density

$$j_e(x) = i(t)/S$$

i(t) - input current (A)

S - area of the conductor (m^2)

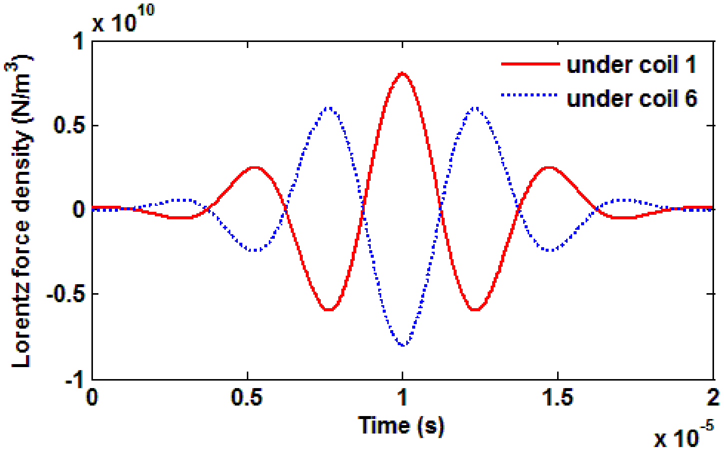


Lorentz Force density

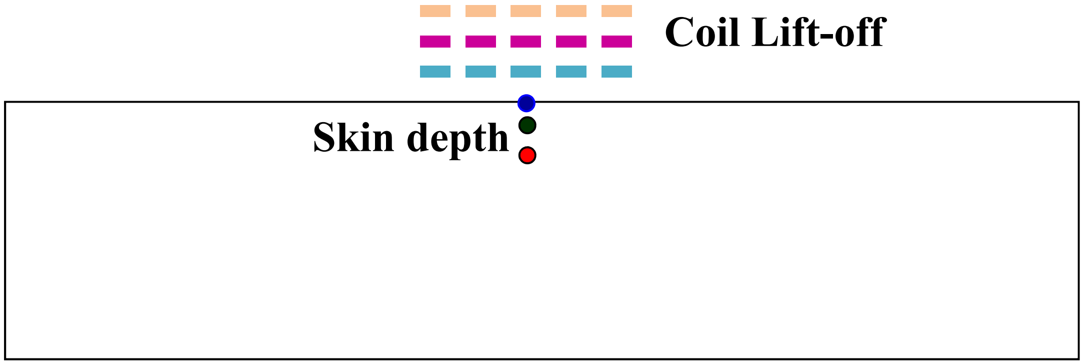
$$F_L(z) = j_e(x) \times B(y)$$

B(y) - applied magnetic field (Tesla)

$j_e(x)$ - input current density (amp/m^2)



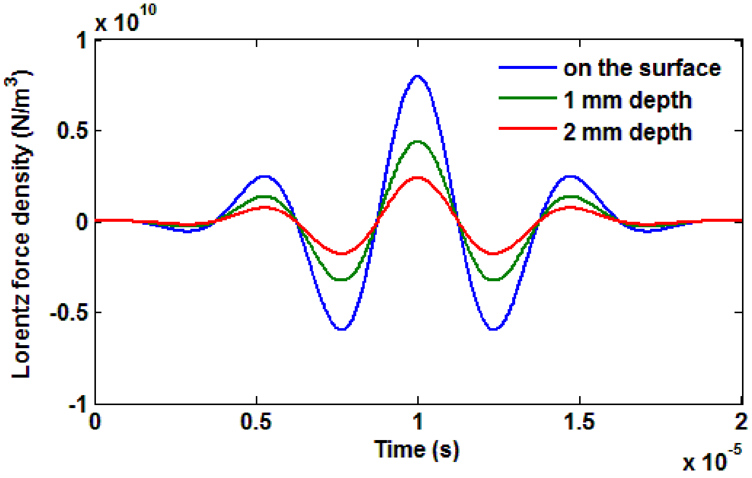
Effect of depth and lift-off variations



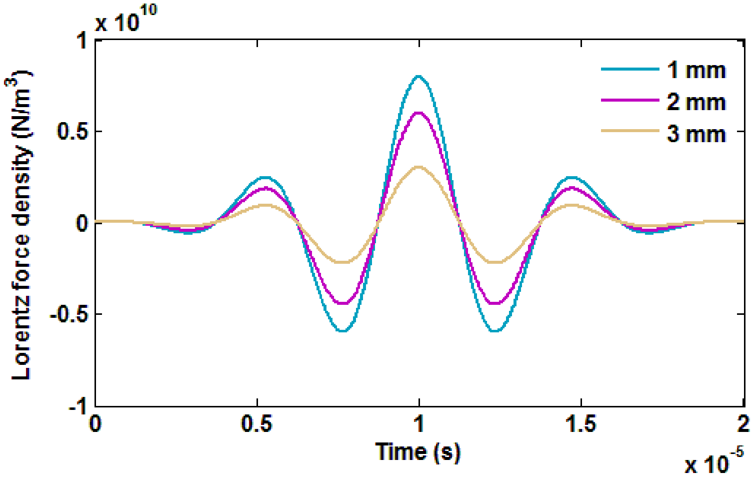
Coil Lift-off

Skin depth

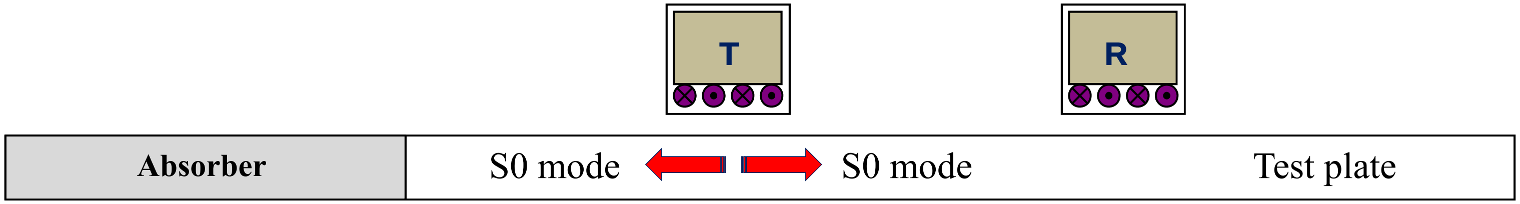
Depth Variation



Lift-off Variation



Acoustic model for Ultrasonic plate waves



- **Length of the element Δ(x)**

  $\Delta(x) = \lambda / 15 \;-\; 0.0004$ m

- **Time step Δ(t)**

  $\Delta(t) = \Delta(x) / C_L \sim 5e\text{-}8$ s

- **Analysis type**

  Transient – plain strain (smpn)

- **Solver type**

  Time dependent – Direct (UMFPACK)

Material : Stainless steel

E = 205 Gpa

$\mu = 0.33$

Density = 7850 Kg/m^3

$C_L = 5680.183$ m/s

$C_T = 3040.923$ m/s

Thickness = 5 mm

Length = 1000 mm

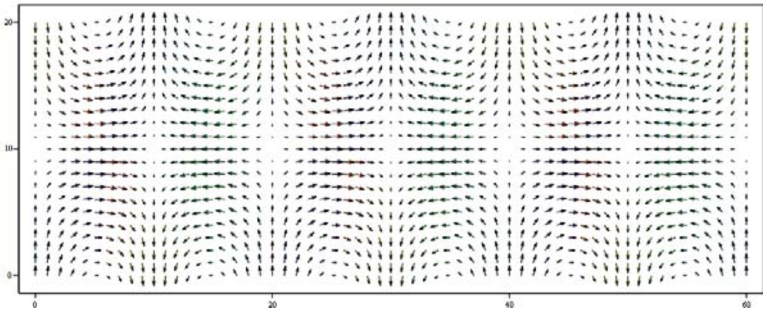
Frequency = 200 kHz

Plate or Lamb waves

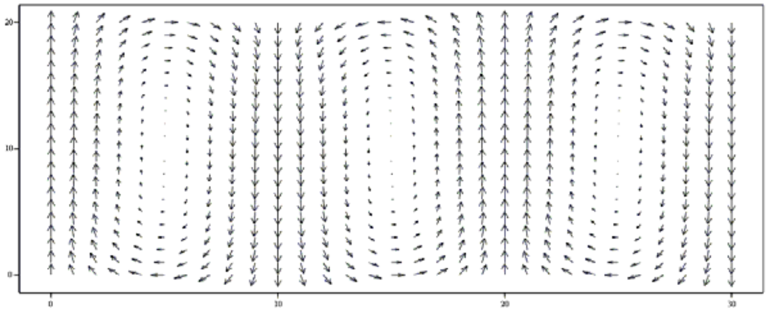
- Plate waves or Lamb waves are elastic perturbations propagating in a solid plate (or layer) with free boundaries, for which displacements occur both in the direction of wave propagation and perpendicularly to the plate of the plate.
- There are two basic forms of lamb waves:

  Symmetrical (Dilatational) and Asymmetrical (Bending)

Symmetric mode Lamb wave



Asymmetric mode Lamb wave



Rayleigh damping

The Rayleigh (proportional) damping model expresses the damping matrix [C] as a linear combination of the mass [M] and the stiffness [K] matrices, that is

$$[C] = \alpha [M] + \beta [K]$$

Where α and β the mass and stiffness damping parameters, respectively. At any frequency (ω), this corresponds to a damping factor (ξ) given by,

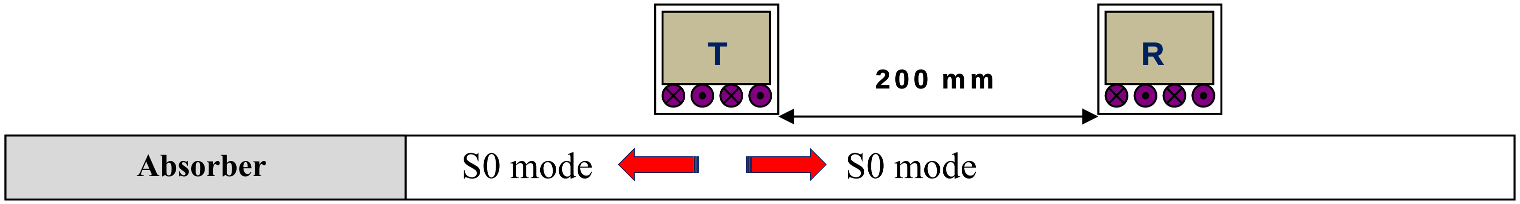
$$\xi = \frac{1}{2}\left(\frac{\alpha}{2\omega} + \beta\omega\right) \quad \Longrightarrow \quad \begin{bmatrix} \dfrac{1}{(2\omega_1)} & \dfrac{\omega_1}{2} \\ \dfrac{1}{(2\omega_2)} & \dfrac{\omega_2}{2} \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \begin{bmatrix} \xi_1 \\ \xi_2 \end{bmatrix}$$

The damping parameters for this model are,

$$\begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \begin{bmatrix} 9.4248e4 \\ 0.000000 \end{bmatrix}$$

Caughey, T. K., “Classical normal modes in damped linear dynamic systems.“, *Transactions of ASME, Journal of Applied Mechanics*, 27, 269-271, 1960.

Generation of plate wave - S0 mode



T

R

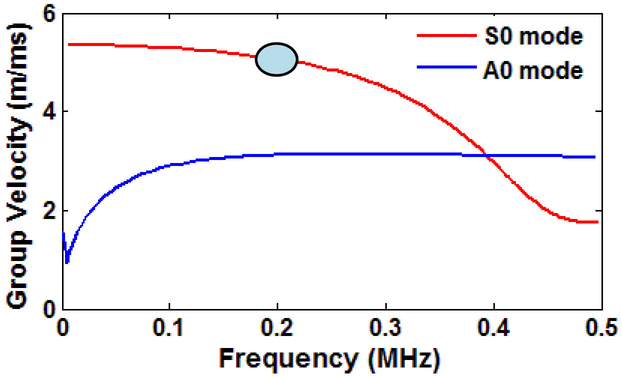
200 mm

Absorber

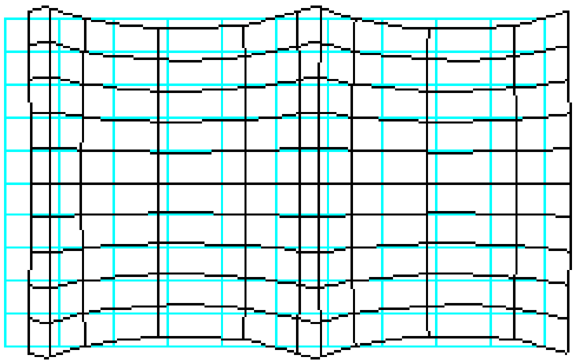
S0 mode

S0 mode

Dispersion Curve



Mode shape of S0 mode



Frequency – 200 kHz

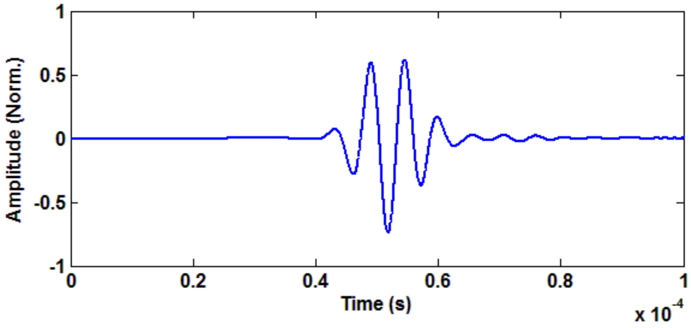
Group velocity – 5064 m/s

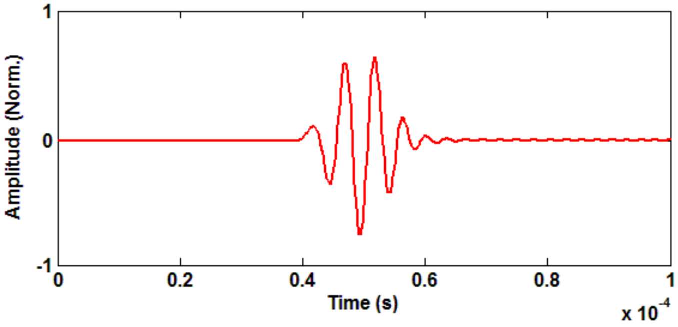
DISPERSE $^{@}$ User manual and Introduction Version 2.0, NDTL, Imperial College, London

Analysis of plate wave (S0) mode

COMSOL@3.5a **DISPERSE@2.0**

A scan signal (S0 mode)



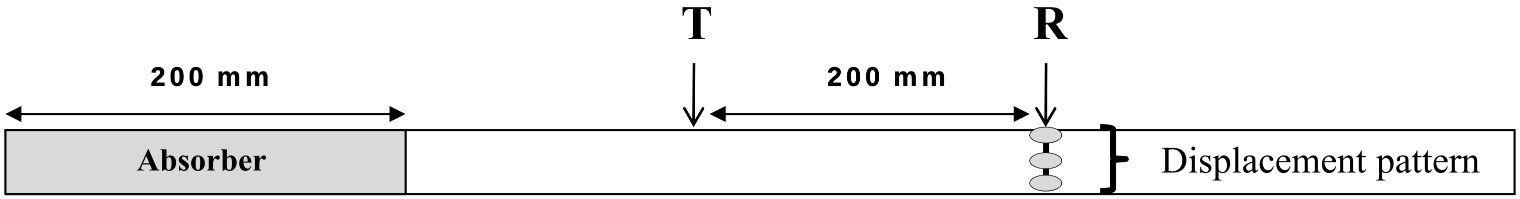


$$\textbf{Group Velocity } (V_{Gp}) = \frac{\textbf{Distance}}{\textbf{Time of flight (TOF)}}$$

Group Velocity (V_{Gp}) = 5066 m/s (**COMSOL**)

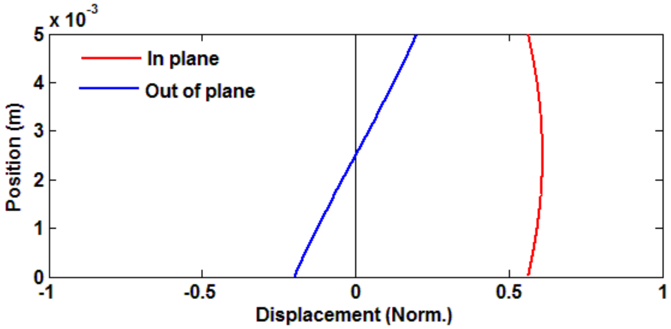
Group Velocity (V_{Gp}) = 5064 m/s (**DISPERSE**)

Comparison with Dispersion curve



COMSOL@3.5a **DISPERSE@2.0**

Displacement profiles



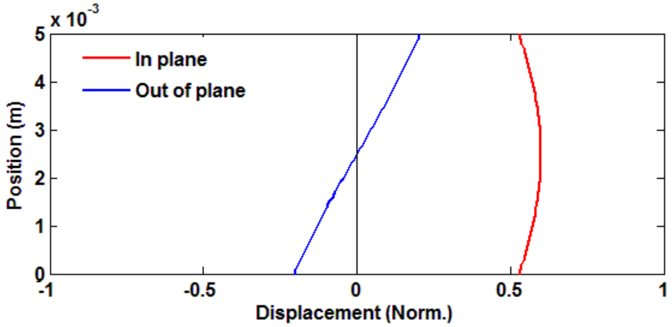
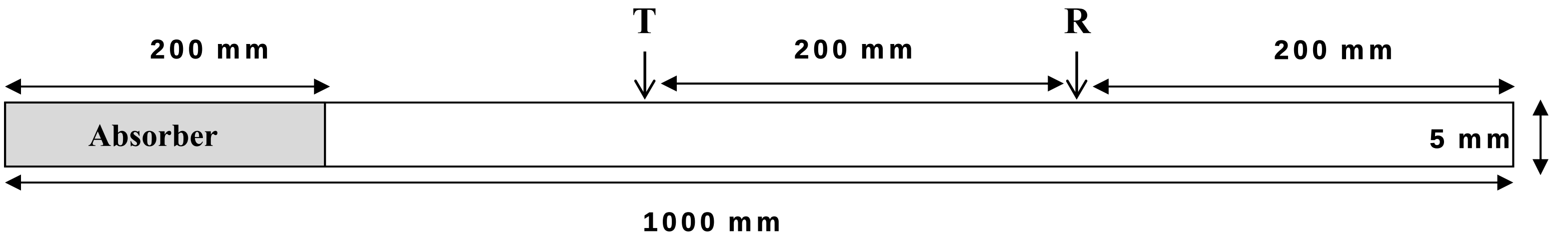
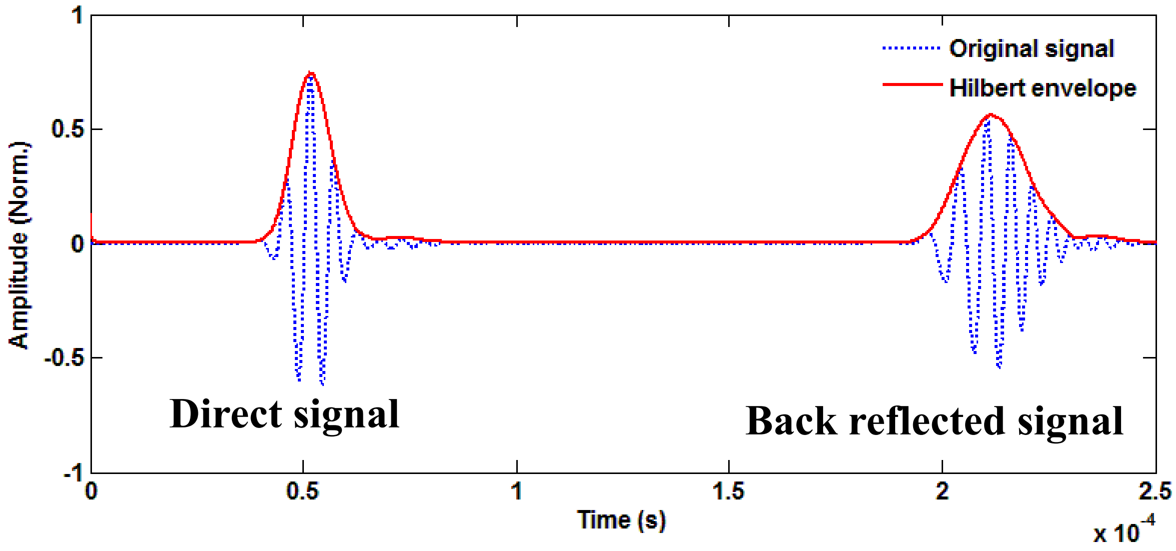
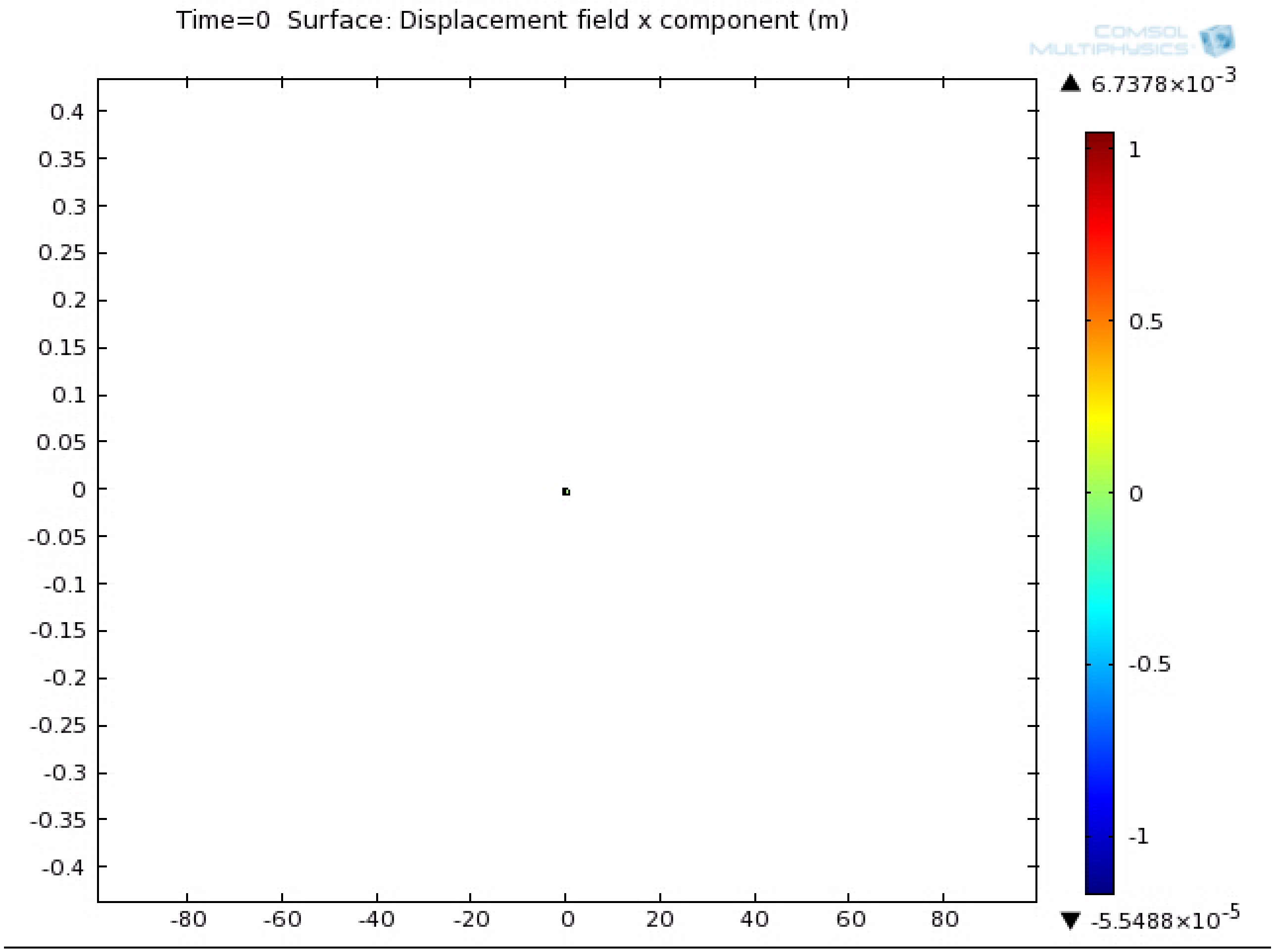


Plate wave mode with Hilbert envelop

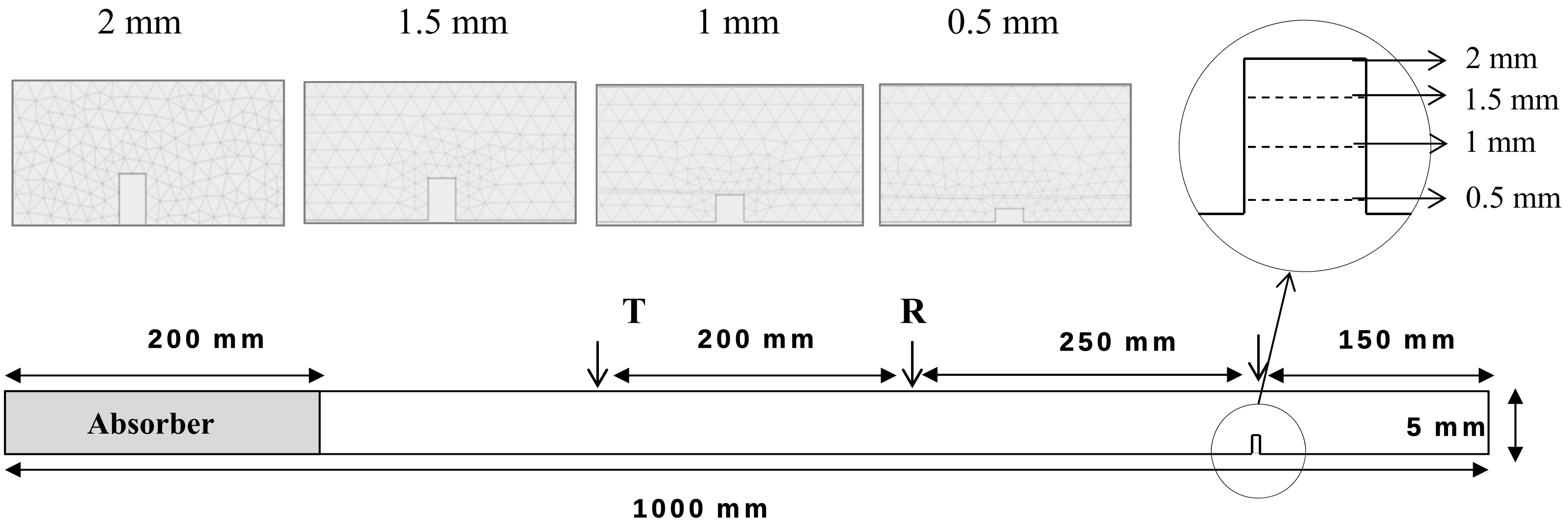




Animation of plate wave (S0) mode



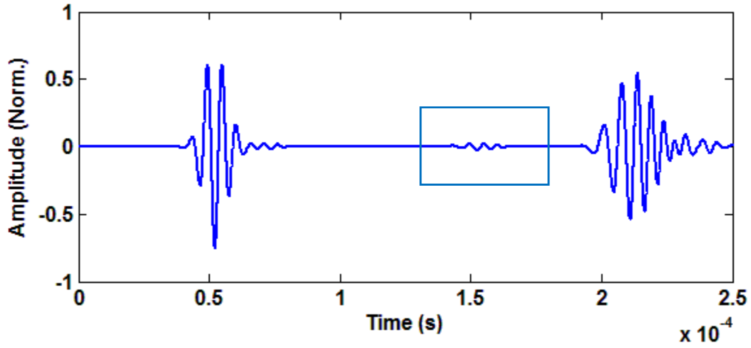
Defect detection using S0 mode



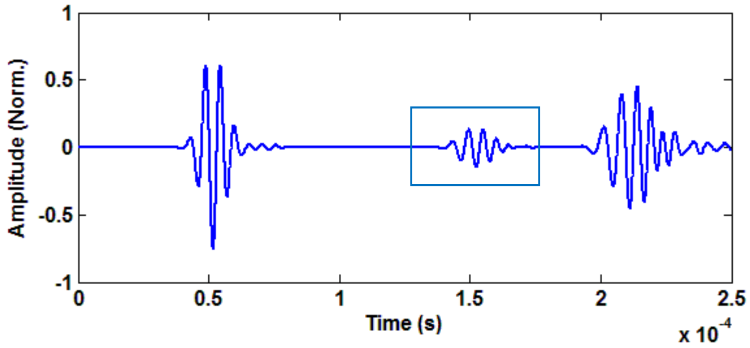
Defect width - 1 mm **Defect height – from 0.5 mm to 2 mm**

Interaction of SO mode with defects

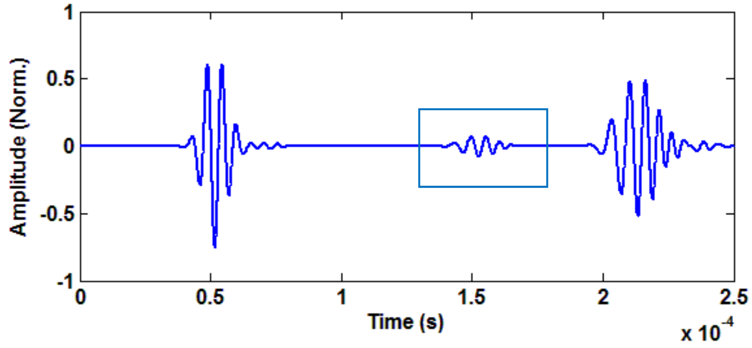
0.5 mm defect



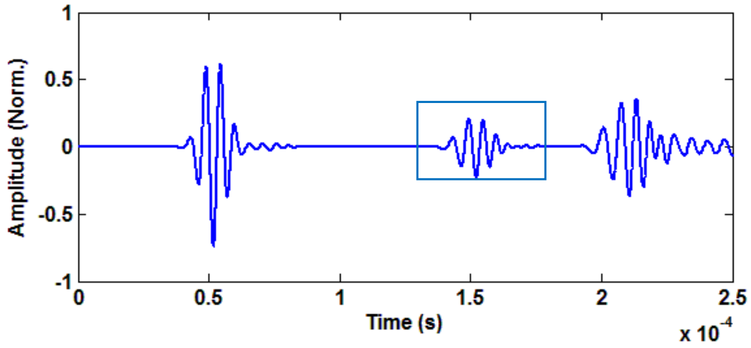
1.5 mm defect



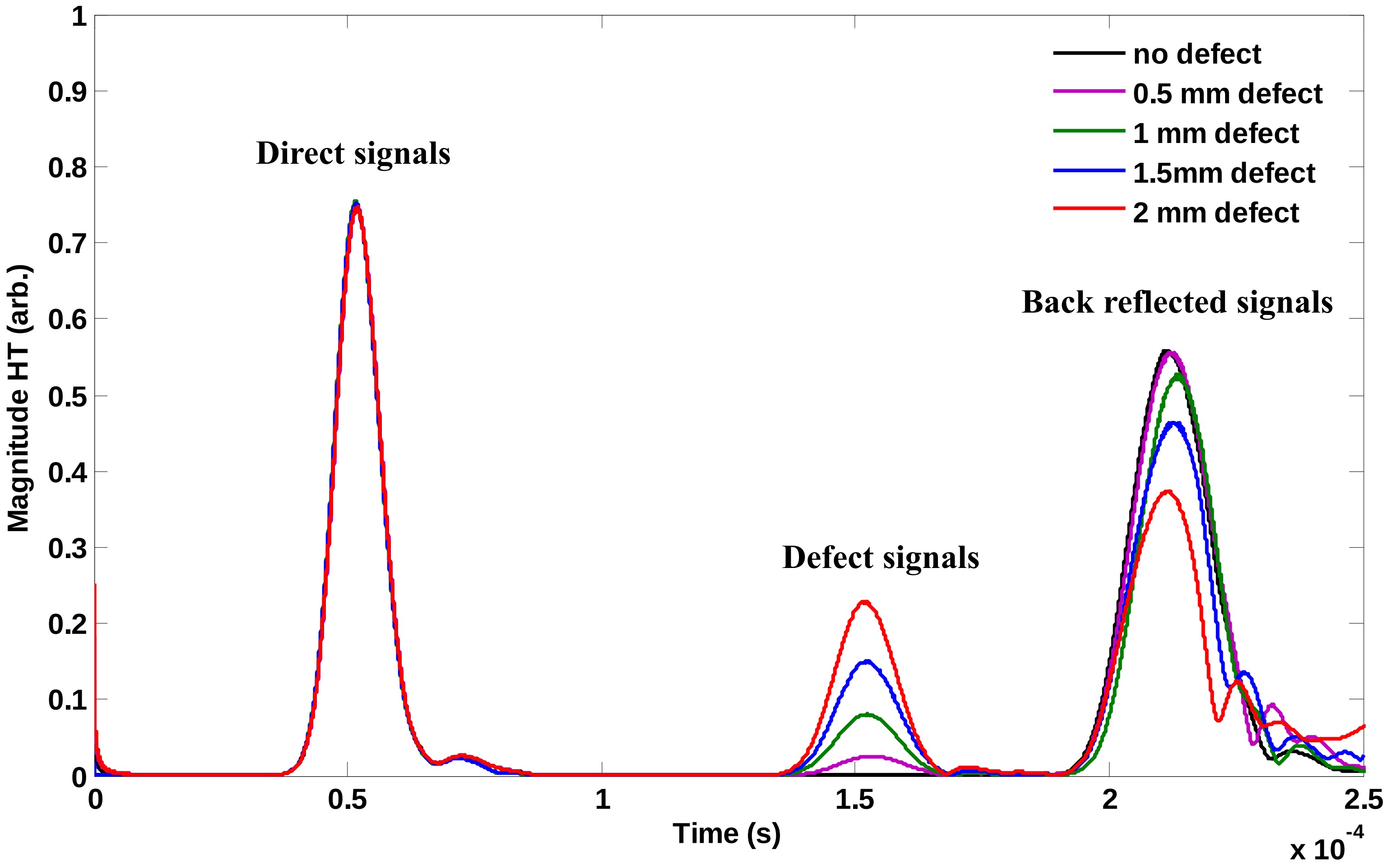
1 mm defect



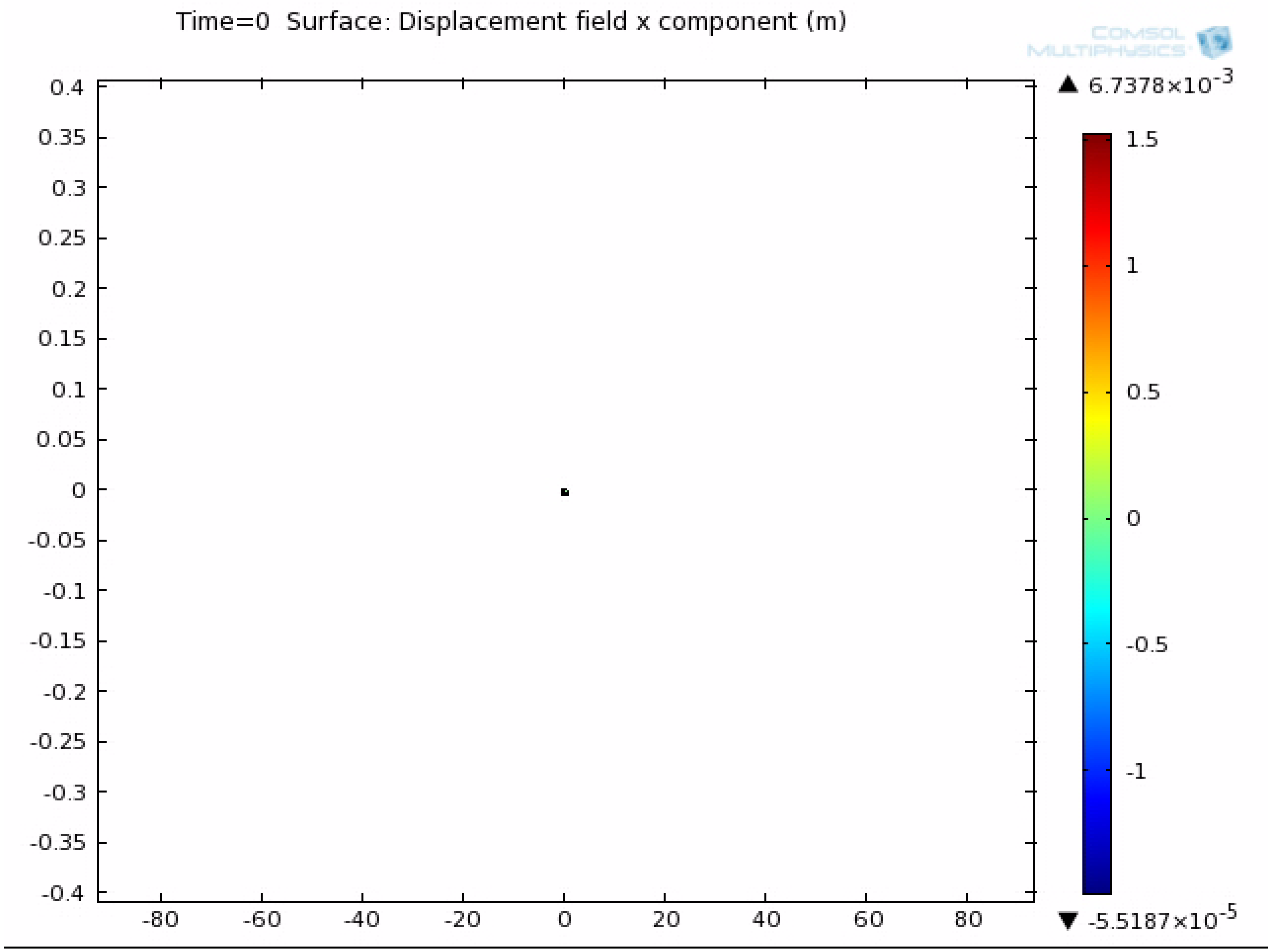
2 mm defect



Defect detection using Hilbert envelope



Animation of S0 mode interaction with defect (2 mm defect)



Summary and Conclusion

- A coupled 2D FE modeling system has been designed for a pulsed spiral coil EMAT which works under the principle of Lorentz force mechanism using the multiphysics software COMSOL® 3.5a.
- The electromagnetic model has been designed for the Lorentz force density calculation. The effects of coil lift-off and skin depth variation have also been observed for the EMAT example. This results indicate that the force computed inside the specimen is a nonlinear function of coil lift-off, and the skin depth.
- The elastodynamic model has been done for the ultrasonic plate wave (S0 mode) generation using the plain stain module. The time of flight (TOF), Group velocity (V_{Gp}) and the displacement profiles of the S0 mode have been analyzed and compared with the Dispersion curves.
- The plate wave (S0) mode has also been used for the defect detection. It has been observed that the defect amplitude increases with the increase in defect height.

Self - References

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Thank you