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The Acoustoelastic Effect: EMAT Excitation and Reception of Lamb Waves in Pre-Stressed Metal Sheets

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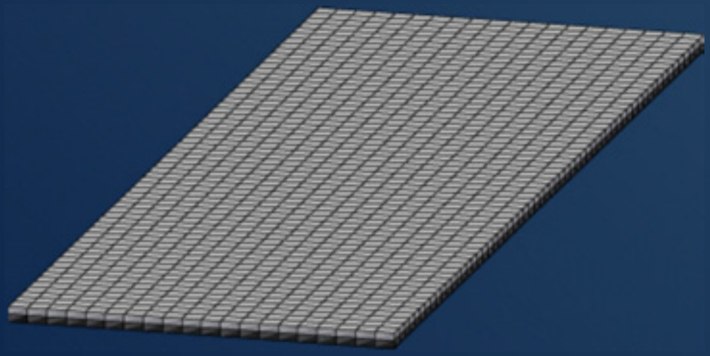
Introduction

- The *acoustoelastic effect* [HK53, TB64] relates the change of acoustic wave *speed* in a solid continuum to its *stress* status
- It is analogous to the better known photoelastic effect
- It can be used to assess *non-destructively* the stress status of a sample, by using *ultrasonic transducers*
- This can be useful in the *metal industry*, for monitoring the process of rolling *metal sheets*

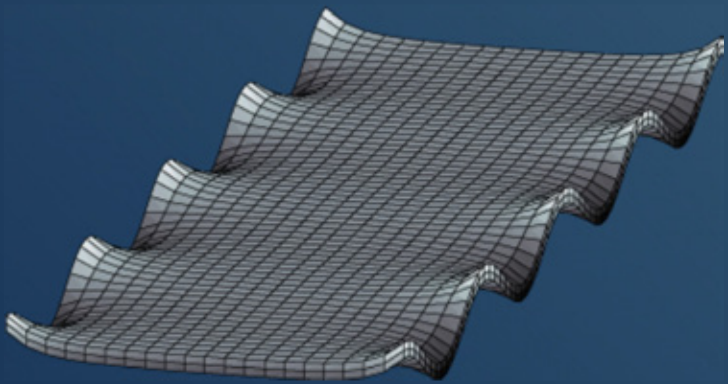
[HK53] D.S. Hughes and J.L. Kelly. Second-order elastic deformation of solids. *Physical Review* , 92(5):1145–1149, Dec. 1953
[TB64] R.N. Thurston and K. Brugger. Third-order elastic constants and the velocity of small amplitude elastic waves in homogeneously stressed media. *Physical Review* , 133(6A):1604–1610, Mar. 1964

Introduction (2)

- For instance, *shape defects* originally present in a metal sheet may show up later as *internal stress non-uniformities*
- In some situations these non-uniformities are the only *visible* clue of the shape defects presence



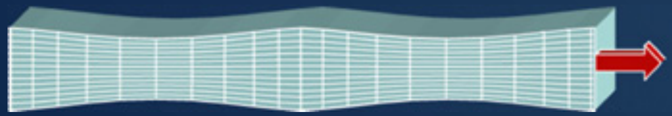
No defect



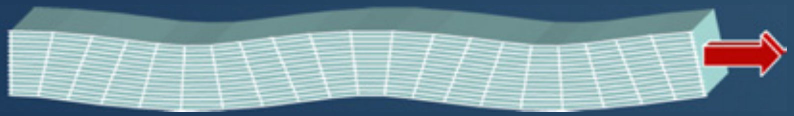
Edge wave defect

Lamb waves

- The *acoustoelastic effect* is very *small*, on the order of one in 10^5 for each applied MPa, for *bulk waves* in common metals
- [DK96] reported effects on the order of one in 10^3 per MPa, for antisymmetric *Lamb waves* in a pre-stressed polymer *foil*
- Lamb waves are guided modes propagating in thin structures, and may be *symmetric* or *antisymmetric* [Vi67]



Symmetric Lamb wave

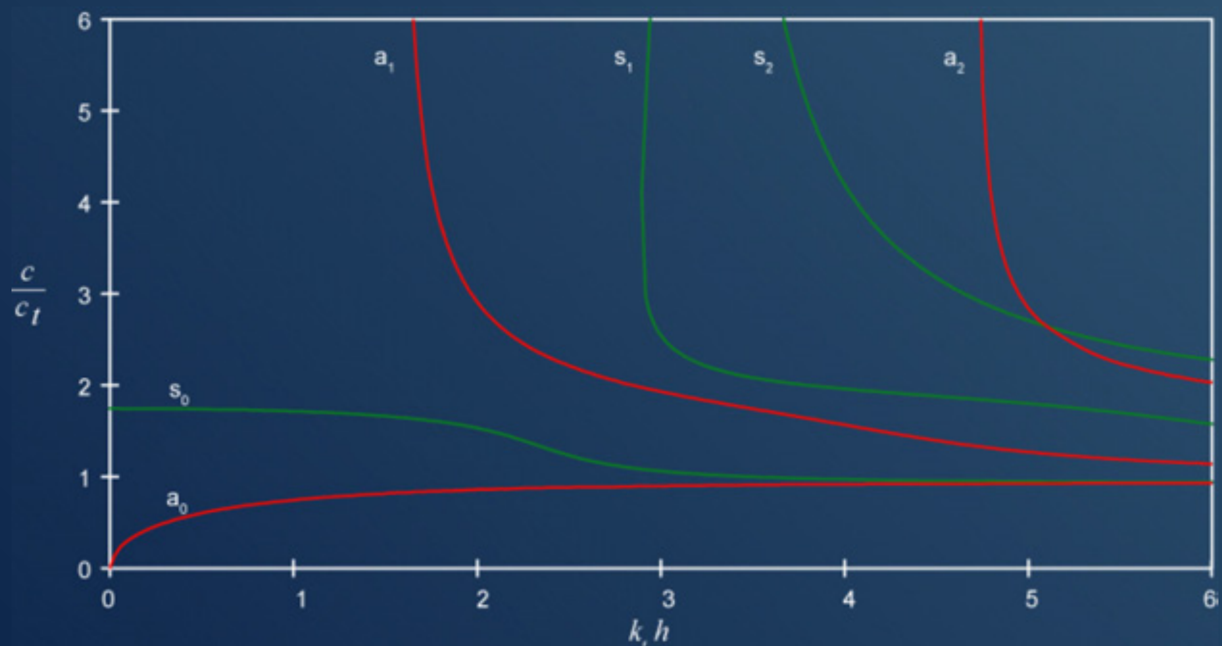


Antisymmetric Lamb wave

[DK96] C. Desmet, U. Kawald, A. Mourad, W. Laurikis, and J. Thoen. The behaviour of Lamb waves in stressed polymer foils. *J. Acoust. Soc. Am.* , 100(3):1509–1513, Sept. 1996.
[Vi67] I.A. Viktorov. *Rayleigh and Lamb Waves* . Ultrasonic technologies, a series of monographs. Plenum Press, New York, 1967.

Lamb waves (2)

- Lamb waves have characteristic *dispersion relations*
- Only the *fundamental* modes a_0 and s_0 exist at every frequency

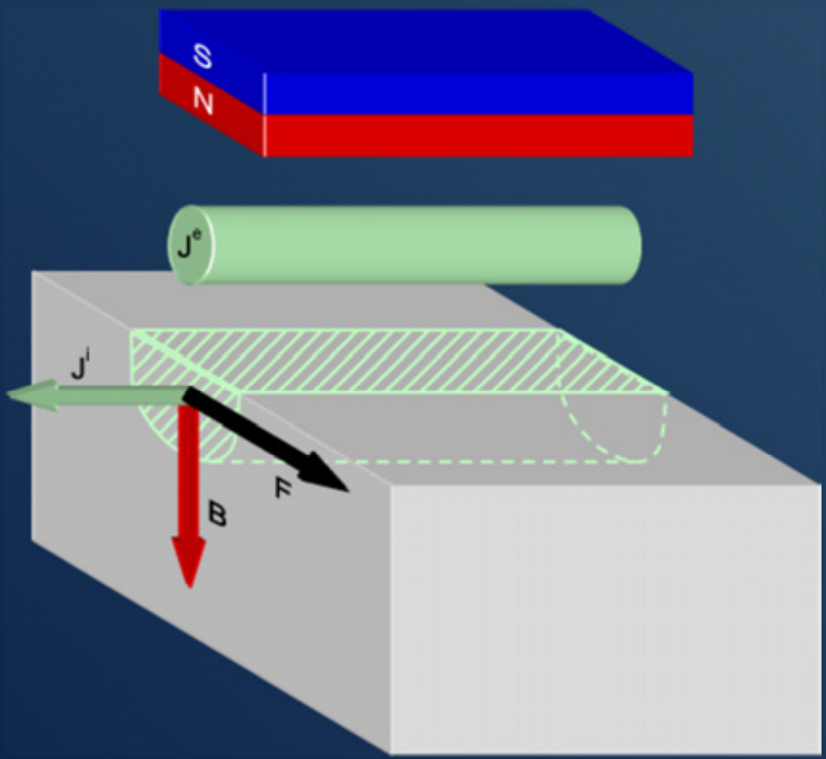


EMATs

- *Contact* transducers may introduce *errors* in the speed measurement greater than the acoustoelastic effect
- Thus *contact-less* transducers such as Laser Ultrasonics [SD90] or *EMATs* [HO03] should be used
- *Electro Magnetic Acoustic Transducers (EMATs)* use a time-varying magnetic field, and an optional static one, to induce a time-varying force in a *conductive* and/or magnetic material
- *Reception* needs a static magnetic field and works on the *Foucault* currents principle

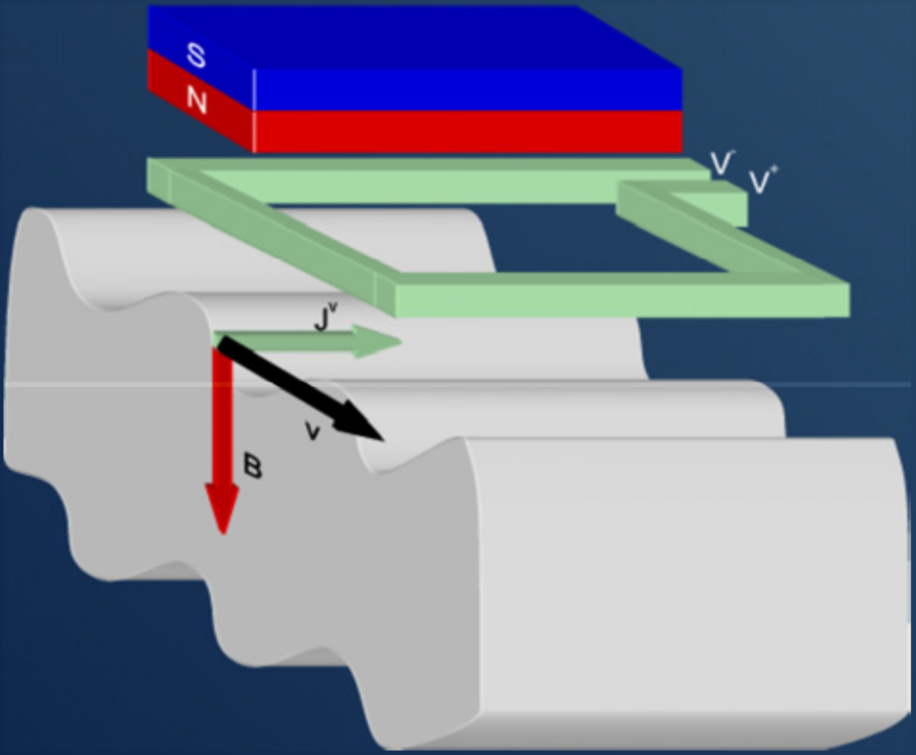
[SD90] C.B. Scruby and L.E. Drain. *Laser Ultrasonics - techniques and applications* . Adam Hilger, Bristol, 1990.
[HO03] M. Hirao and H. Ogi. *EMATs for Science and Industry: Noncontacting Ultrasonic Measurements*. Springer, 2003.

EMATs (TX)



EMAT *generation* of acoustic impulse by means of the *Lorentz Force* mechanism in a conductive, but non-magnetic material

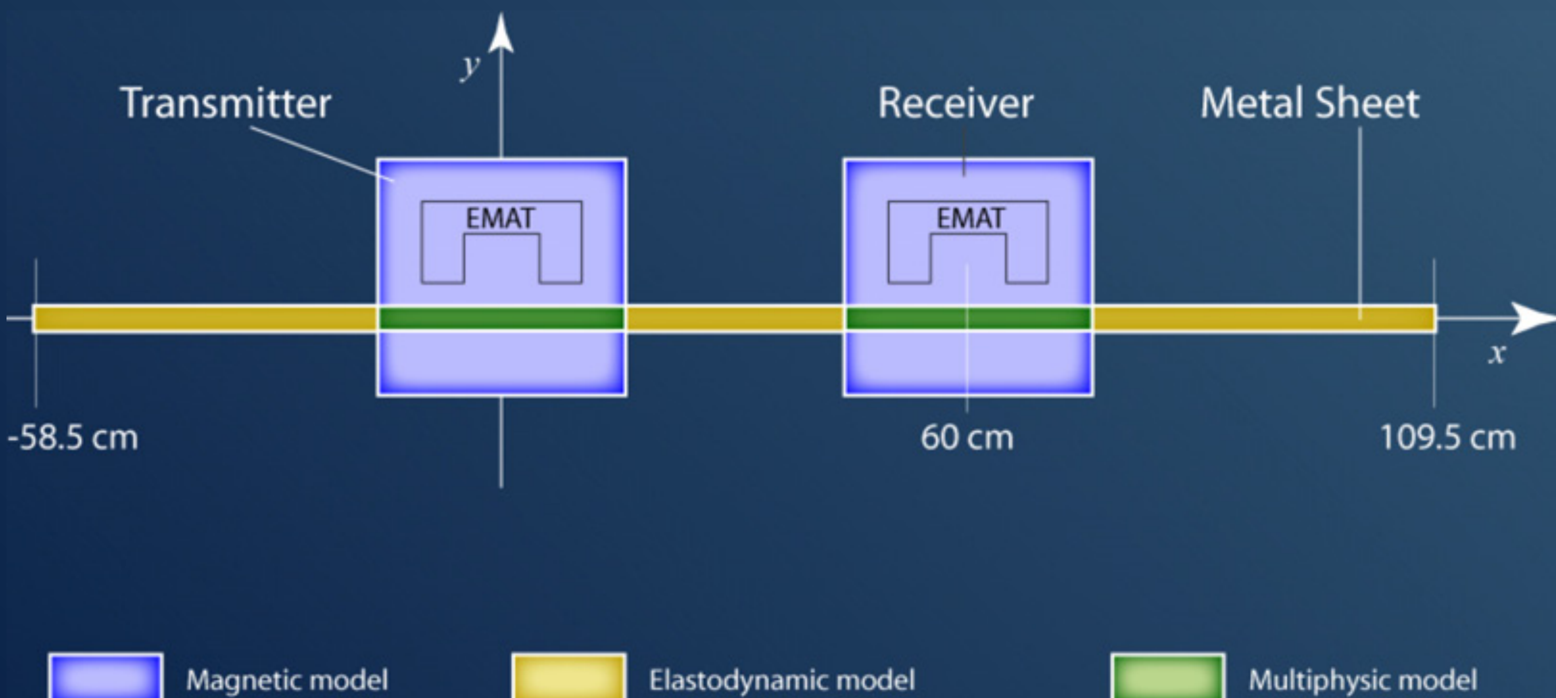
EMATs (RX)



EMAT *reception* of acoustic waves by means of the *Foucault currents* mechanism in a conductive, but non-magnetic material

Modelled setup

- In this work we will develop a *multiphysic* model with two EMATs in a *pitch-catch* setup, and a pre-stressed metal sheet



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Outline

- Acoustoelastic equations
- Modelling acoustoelasticity and EMATs in Comsol
- Effects on Lamb waves excited and received by EMATs

Acoustoelasticity

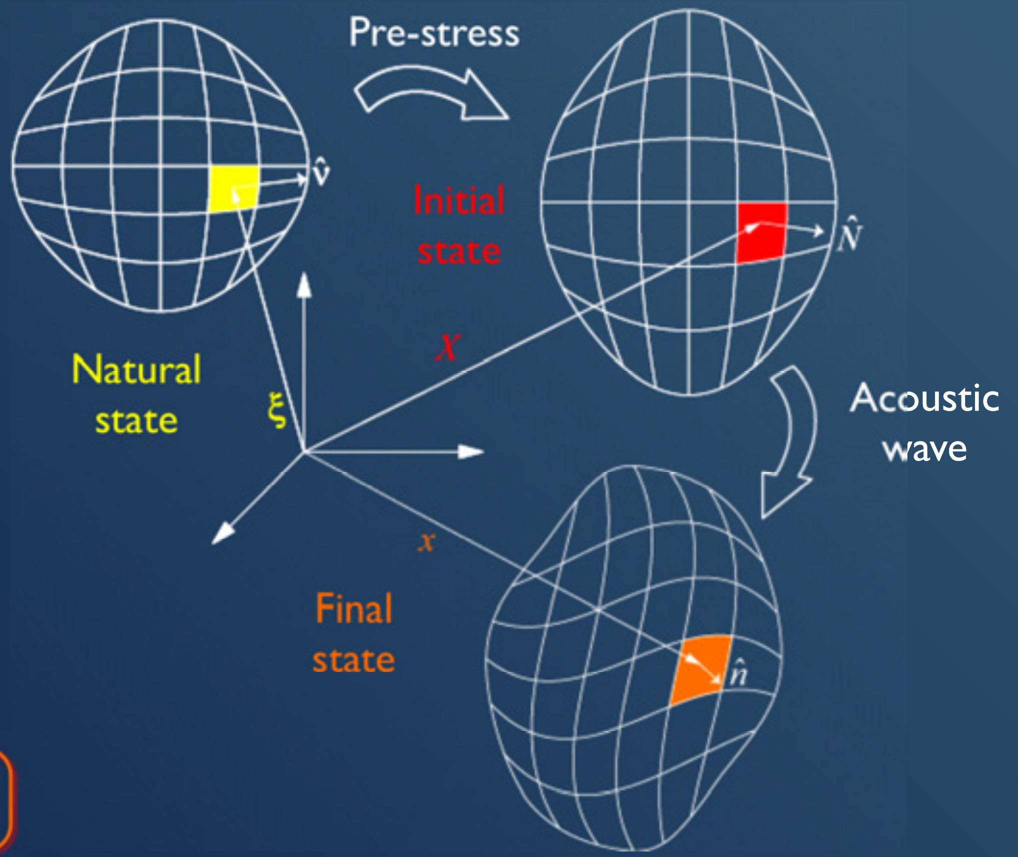
- *Acoustoelasticity* is a *nonlinear* effect relating the change in the propagation *speed* of a *small elastic deformation*, to the amplitude of the pre-existing and underlying (large) deformation
- It is then useful to decompose the deformation of a solid body at any time into two contributions
- To this end, three states of deformation will be considered:
  - *natural state* (no deformation)
  - *initial state* (static large deformation)
  - *final state* (small dynamic deformation overlay on the large static deformation)

Three states

$$u^{(i)} \triangleq X - \xi$$

$$u^{(f)} \triangleq x - \xi$$

$$u \triangleq x - X = u^{(f)} - u^{(i)}$$



Acoustoelasticity equations

- *Dynamic equations* for acoustoelasticity can be written by considering only the *geometric nonlinearity*

$$\frac{\partial \sigma_{ij}^{(f)}}{\partial x_i} + \rho^{(f)} f_j = \rho^{(f)} \ddot{u}_j^{(f)}$$

Dynamic eq.,
final Cauchy stress

$$\frac{\partial}{\partial X_K}\left(S_{KJ}^{(f)} + S_{KL}^{(f)} \frac{\partial u_J}{\partial X_L}\right) + \rho^{(i)} f_j = \rho^{(i)} \ddot{u}_j$$

Dynamic eq.,
final II Piola-Kirchoff stress

$$\frac{\partial}{\partial X_I} S_{IJ} + \sigma_{IL}^{(i)} \frac{\partial^2 u_J}{\partial X_I \partial X_L} + \rho^{(i)} f_J = \rho^{(i)} \ddot{u}_J$$

Dynamic eq.,
incremental II Piola-Kirchoff stress,
initial Cauchy stress

Acoustoelasticity equations (2)

- *Dynamic equations* for acoustoelasticity can be written by considering only the *geometric nonlinearity*

$$S_{IJ} = C_{IJKL} \frac{\partial u_K}{\partial X_L}$$

Constitutive relations

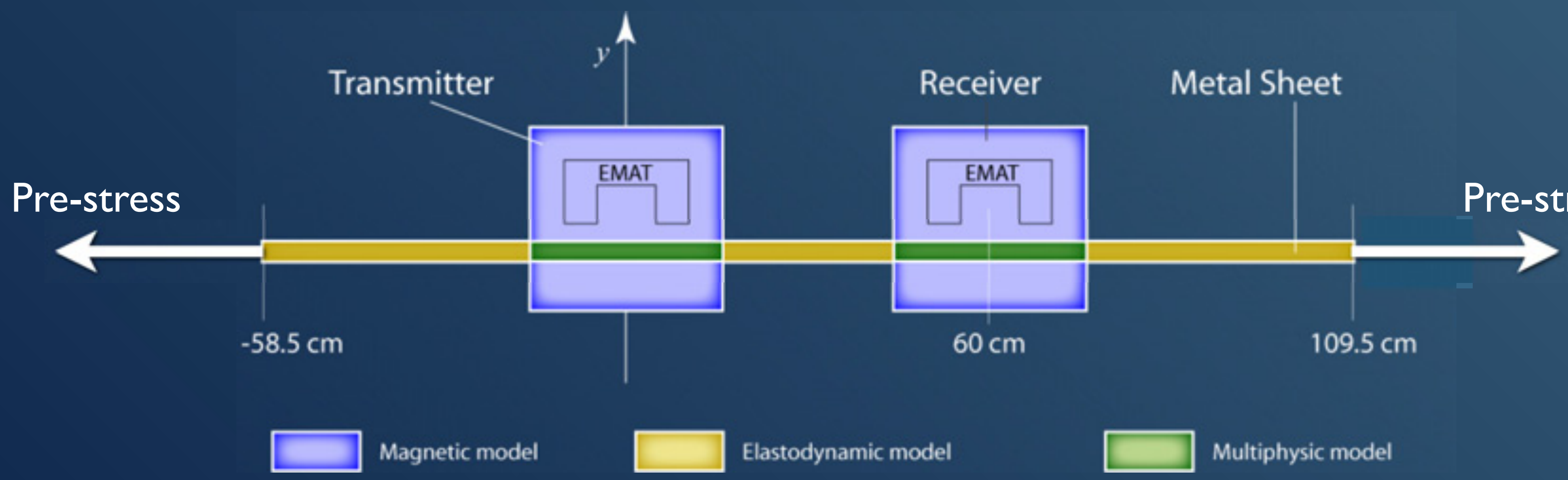
$$C'_{IJKL} \frac{\partial^2 u_K}{\partial X_I \partial X_L} + \rho^{(i)} f_J = \rho^{(i)} \ddot{u}_J$$

Incremental dynamic equation

$$C'_{IJKL} = C_{IJKL} + \sigma_{IL}^{(i)} \delta_{JK}$$

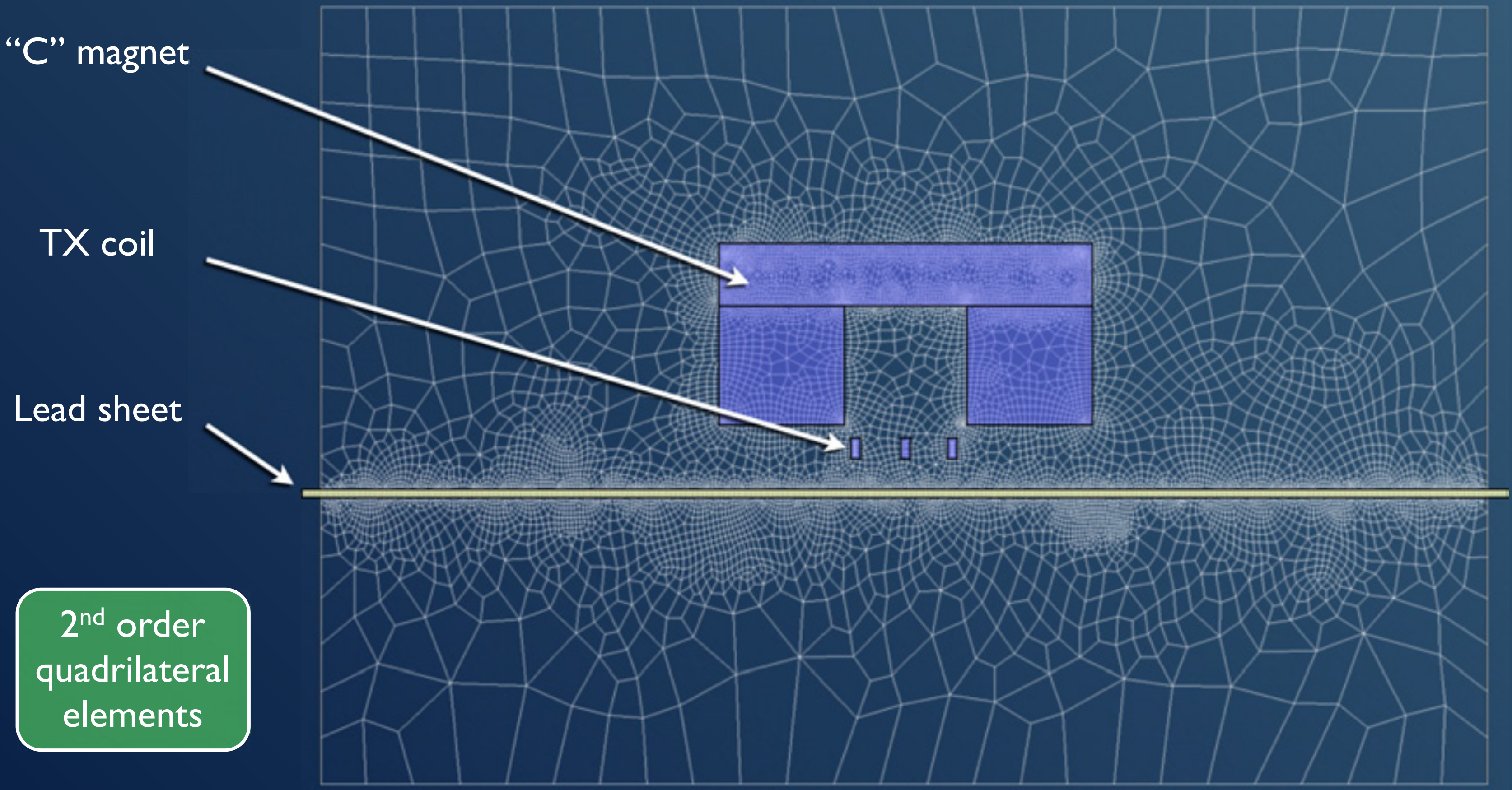
Equivalent stiffness tensor

Comsol Model



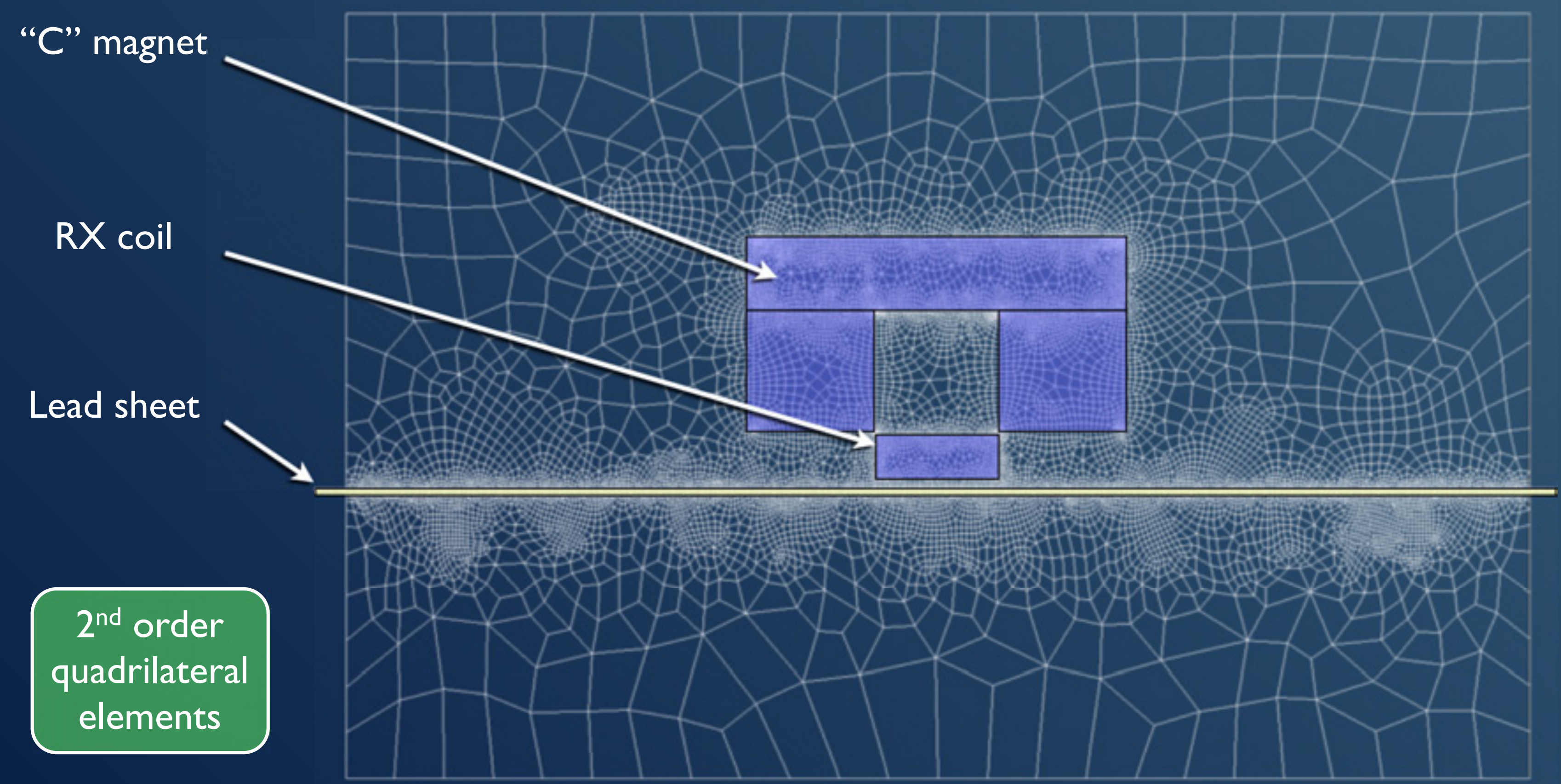
- Four Application modes:
  - 3 *AC/DC* modes (static magnetic fields, TX dynamic field and RX dynamic field)
  - A customized *Structural Mechanics* plane strain mode

EMAT (TX)



2nd order quadrilateral elements

EMAT (RX)



2nd order quadrilateral elements

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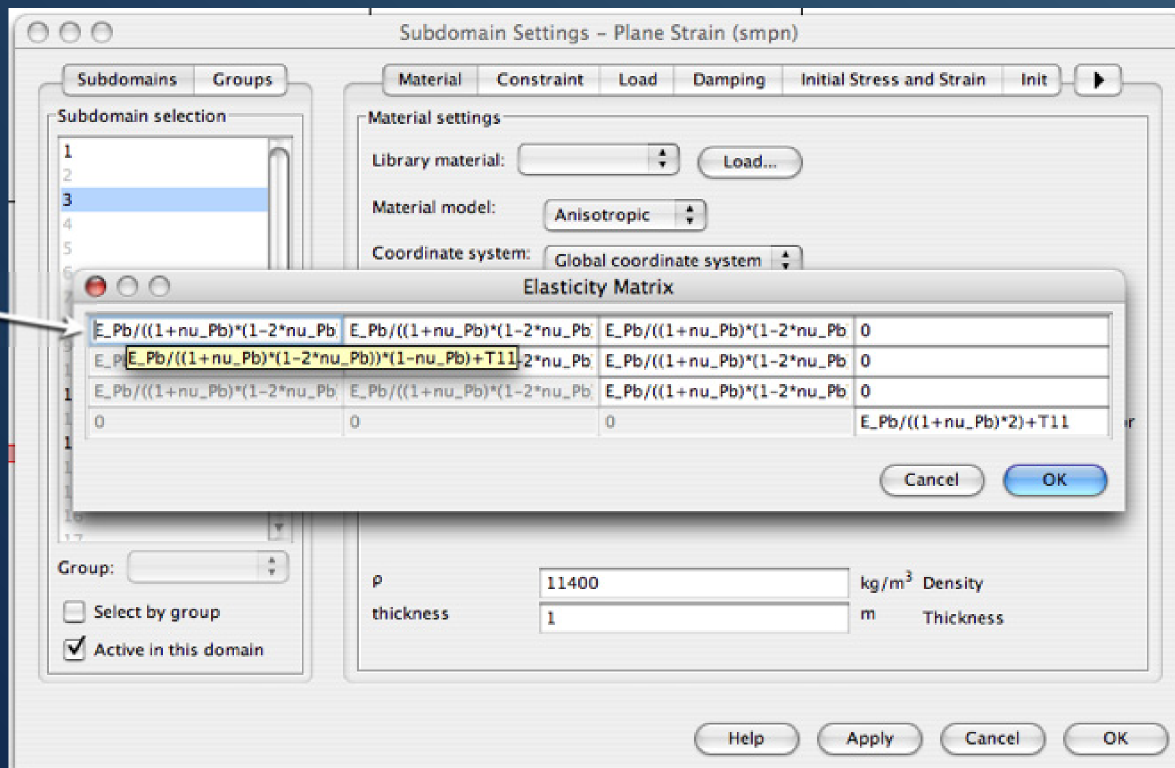
Metal sheet

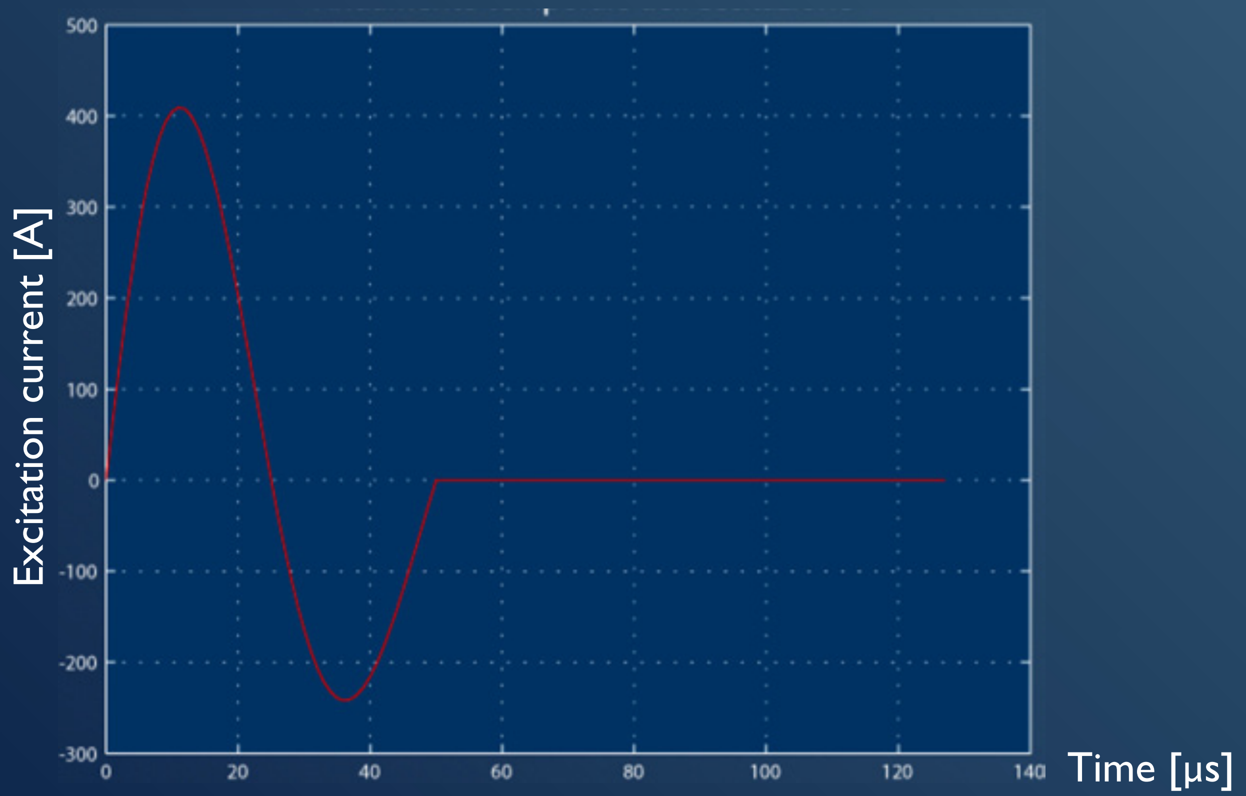
4 rows of linear rectangular elements

The effect of an uni-axial pre-stress T_{11} is described by an anisotropic equivalent stiffness tensor



Results

- The TX EMAT is subjected to one cycle of a 20 KHz damped sinusoidal current



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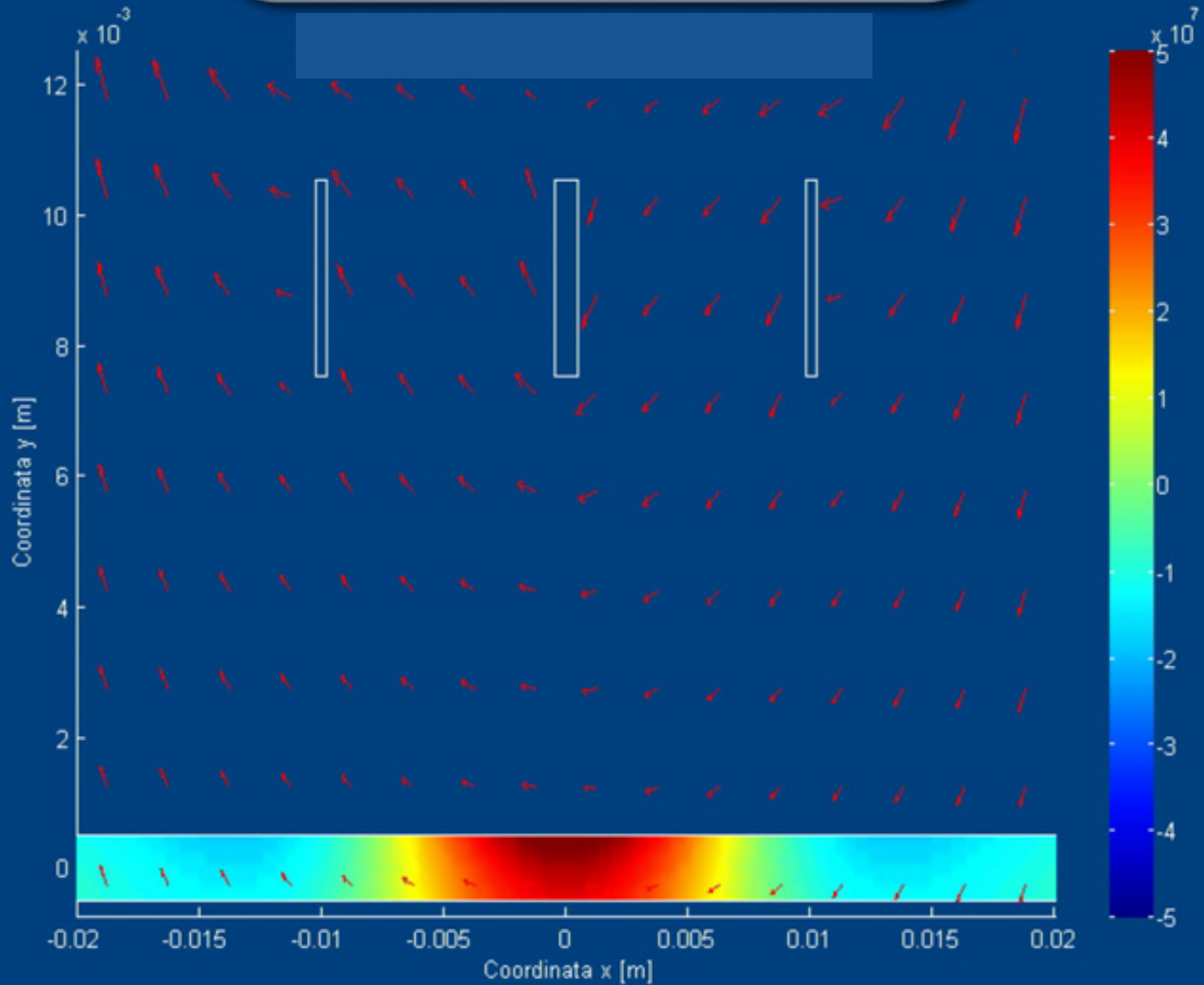
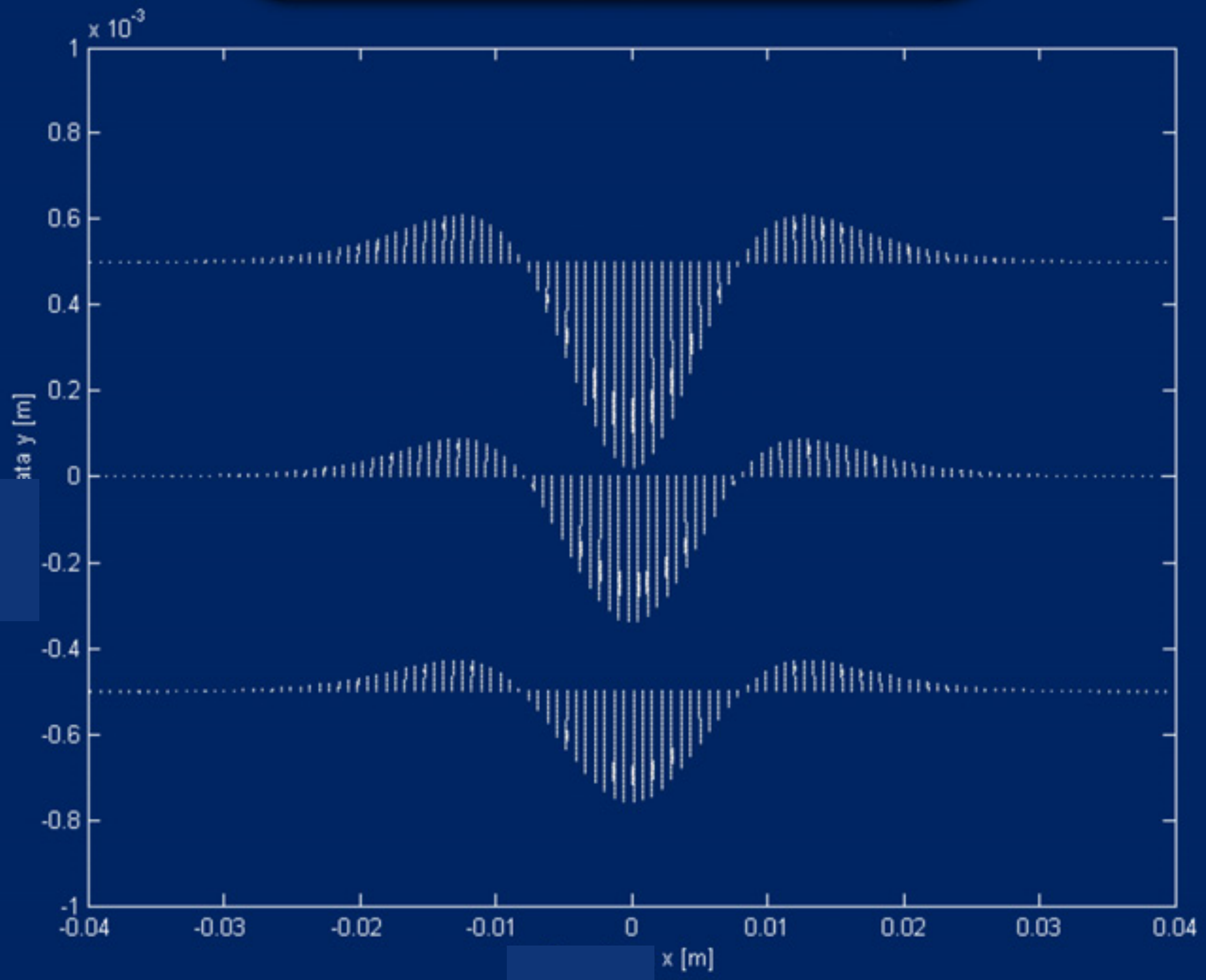
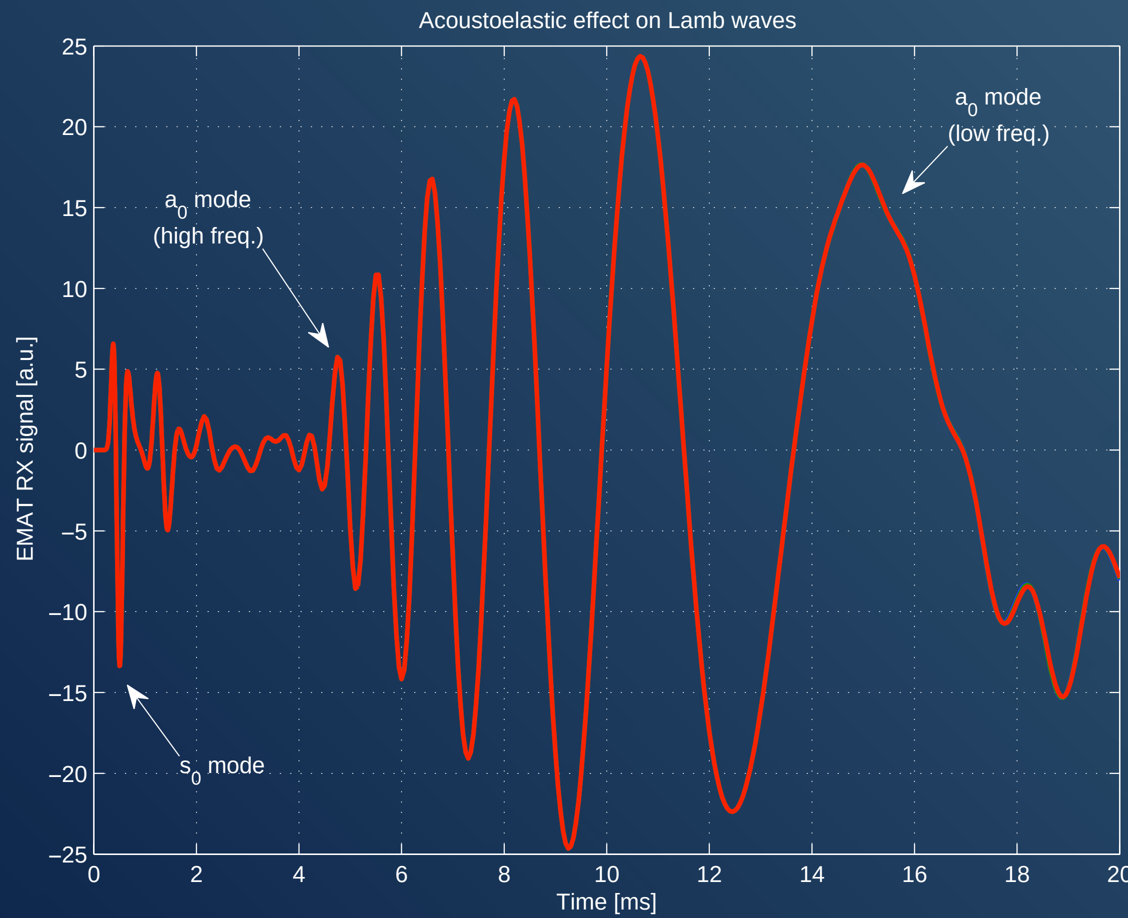
EMAT TX field



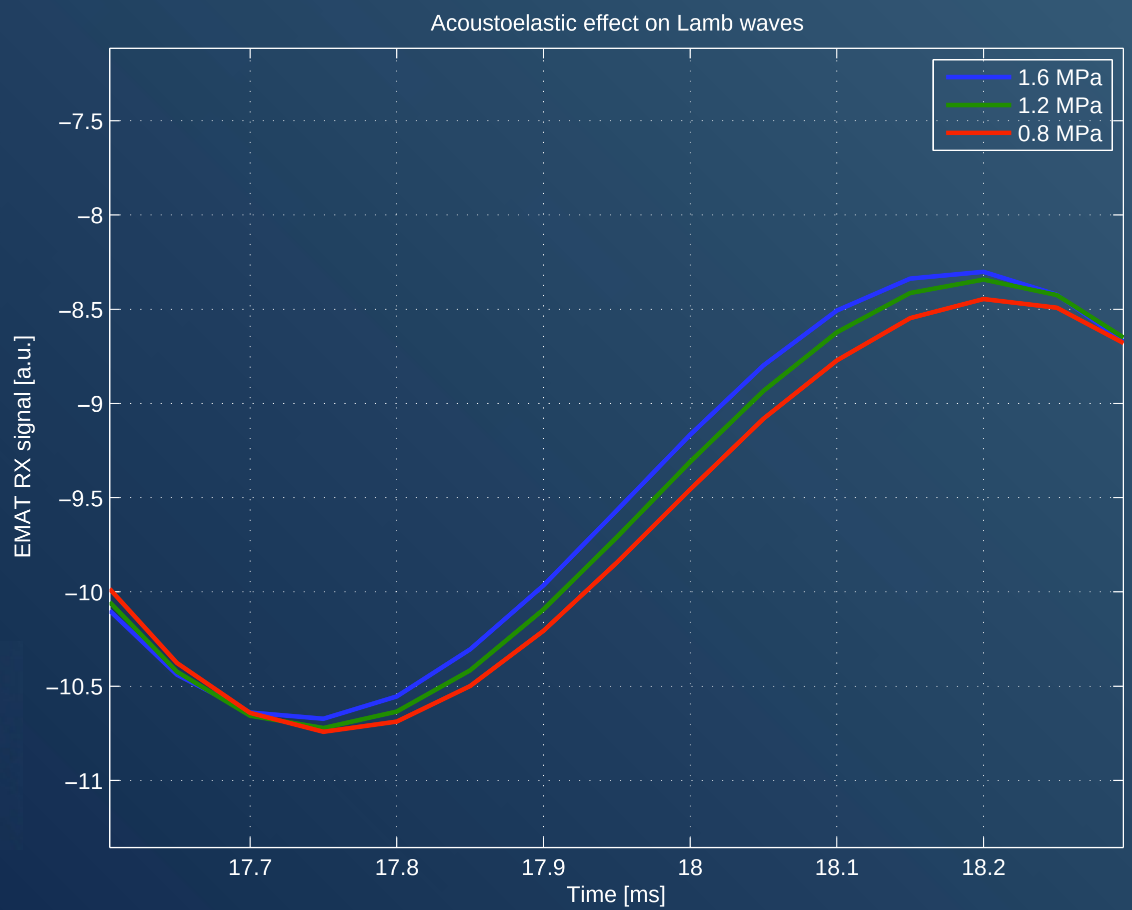
EMAT TX force



EMAT RX signal



EMAT RX signal



For the plotted frequency component of the a_0 wave, the change in speed is about 2/1000th per MPa

Conclusion

- A Multiphysics model was presented accounting for EMAT transmission and reception of ultrasonic waves
- The acoustoelastic effect was included in a custom mode based on the Structural Mechanics Plane Strain
- Simulated data confirms previously published results on Lamb wave behaviour in pre-stressed media

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Further info

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