EDDY CURRENT MODELING OF FERRITE-CORE PROBES, APPLICATION TO THE SIMULATION OF EDDY CURRENT SIGNALS FROM SURFACE BREAKING FLAWS IN AUSTENITIC STEEL

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Abstract: The CEA has developed a fast model for the simulation of ferrite-cored probes. This model is based on the formalism of the Green's dyadic functions. It can be used for the design of new probes and for the simulation of Eddy Current (EC) signals. This paper presents the simulation of EC signal from surface breaking flaws in austenitic stainless steel. The effect of the ferrite core is analyzed in the normalized impedance diagram and the distribution of the EC in an austenitic slab is given for a ferrite-cored probe. It is shown that the responses of an absolute coil and of a transmit/receive probe can be significantly different regarding to the length of a notch. The model has been validated by comparison with experimental data in the framework of a joint project between CEA and EDF aimed at the characterization of the depth of surface breaking flaws in austenitic stainless steel 304L. The simulation of absolute, differential and transmit/receive probe with ferrite core will be integrated in the Non Destructive Testing (NDT) platform CIVA.

Introduction: Eddy Current testing is very efficient for the detection of surface breaking flaws in conductive materials. The characterization of the flaws is however a more difficult task: the phase of the EC signals has a very low range of variation with respect to the depth of the flaw and the amplitude is strongly affected both by the length and the depth of the flaw. The use of a fast simulation tool can significantly ease this characterization process. The response of a probe with respect to its geometry and working conditions can be quickly simulated for a number of parameters such as length, depth, width and shape of a notch. The response of two specific probes: a small absolute Z-probe and a larger Transmit/Receive probe have been investigated for the inspection of stainless steel 304L. The experimental data were collected during a joint project between CEA and EDF. The simulation tool is derived from the CIVA Eddy Current model. It is based on Volume Integral Method (VIM) and has been recently extended to the case of probes with ferrite core in the frame of a collaboration with EADS [1].

Characterization of the probes in the normalized impedance diagram: The normalized impedance diagram is defined as a plot of the impedance of a coil over a conductive material normalized by its inductive reactance in air (X_0). The normalized inductive reactance (X/X_0) and the normalized resistance (R/X_0) are plotted for a set of frequencies. The coupling between the probe and the material is usually optimum when R/X_0 is maximized. The corresponding frequency can then be selected for the inspection.

Let us consider two different kinds of probes: a small absolute Z-probe (defined in figure 1 and called Probe 1) and a larger Transmit/Receive probe (defined in figure 2 and called Probe 2).

The normalized impedance diagram for Probe 1 without ferrite core is given in figure 3 and, keeping the same scale, in figure 4 with a ferrite core. The ferrite core improves clearly the coupling effect as can be seen from the large curve shift toward high values of normalized resistance (R/X_0). Accordingly to the probe characteristics shown in the diagram of figure 4, the working frequency was set to 1 MHz. Probe 2 works in Transmit/Receive mode and the EC signal is directly proportional to the changes of mutual between transmitter and receiver coils. However, the normalized impedance diagram gives a quantitative evaluation of the coupling of the transmitter with the material and so can be used to choose the frequency. With respect to this diagram (figure 5), the working frequency was set to 100 kHz for Probe 2.

Eddy Currents induced in the slab: The distribution of the Eddy Currents in a stainless steel slab (type 304L) for the working frequencies is shown in figure 6 for Probe 1 and in figure 7 for Probe 2. The flux density inside the ferrite core is also plotted (the magnitude is given by a color scale and the direction by arrows).

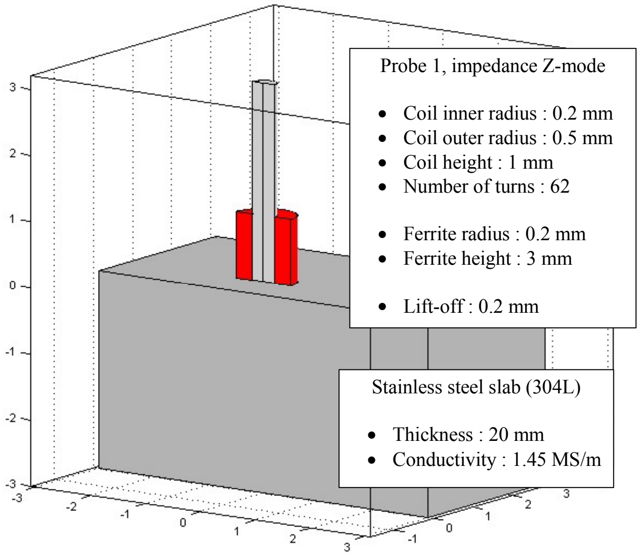


figure 1 : characteristics of Probe 1
(impedance Z-Mode)

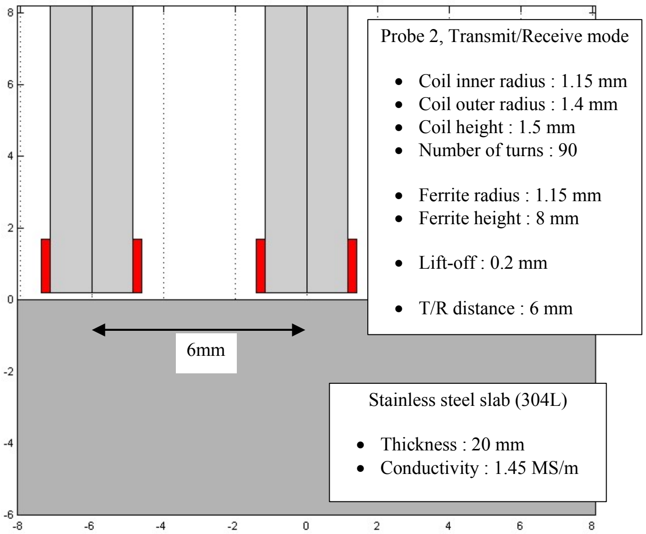


figure 2 : characteristics of Probe 2
(Transmit/Receive mode)

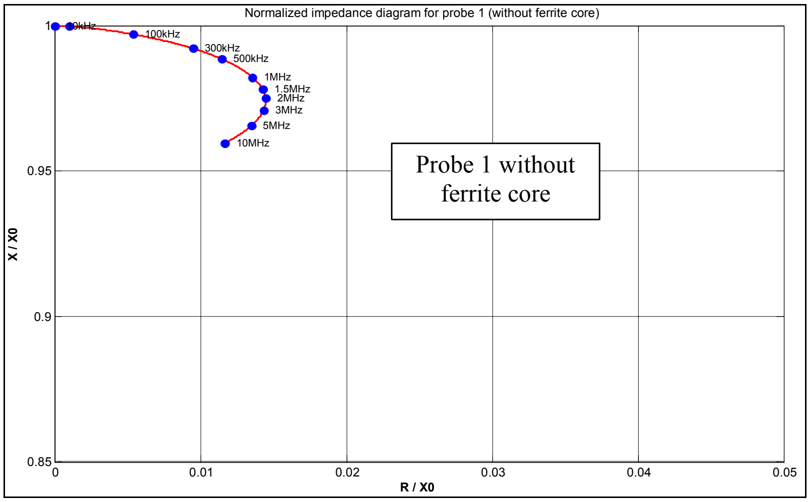
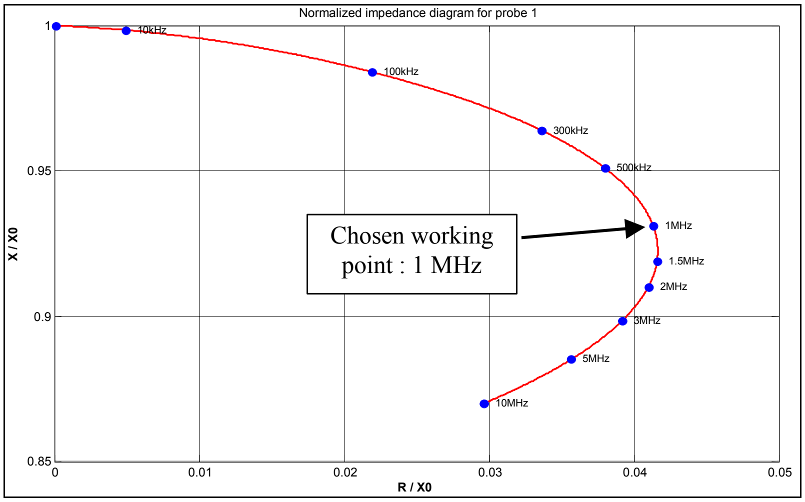
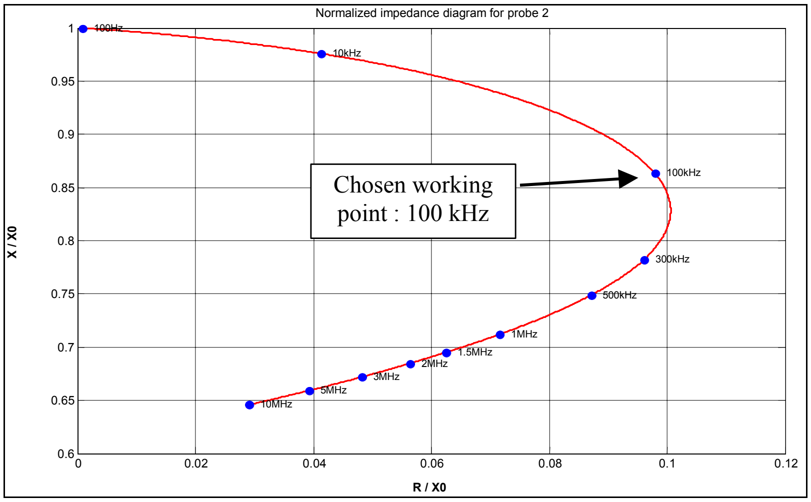


figure 3 : normalized impedance diagram for Probe 1, **without ferrite core**



Chosen working point : 1 MHz

figure 4 : normalized impedance diagram for Probe 1



Chosen working point : 100 kHz

figure 5 : normalized impedance diagram for Probe 2 transmitter

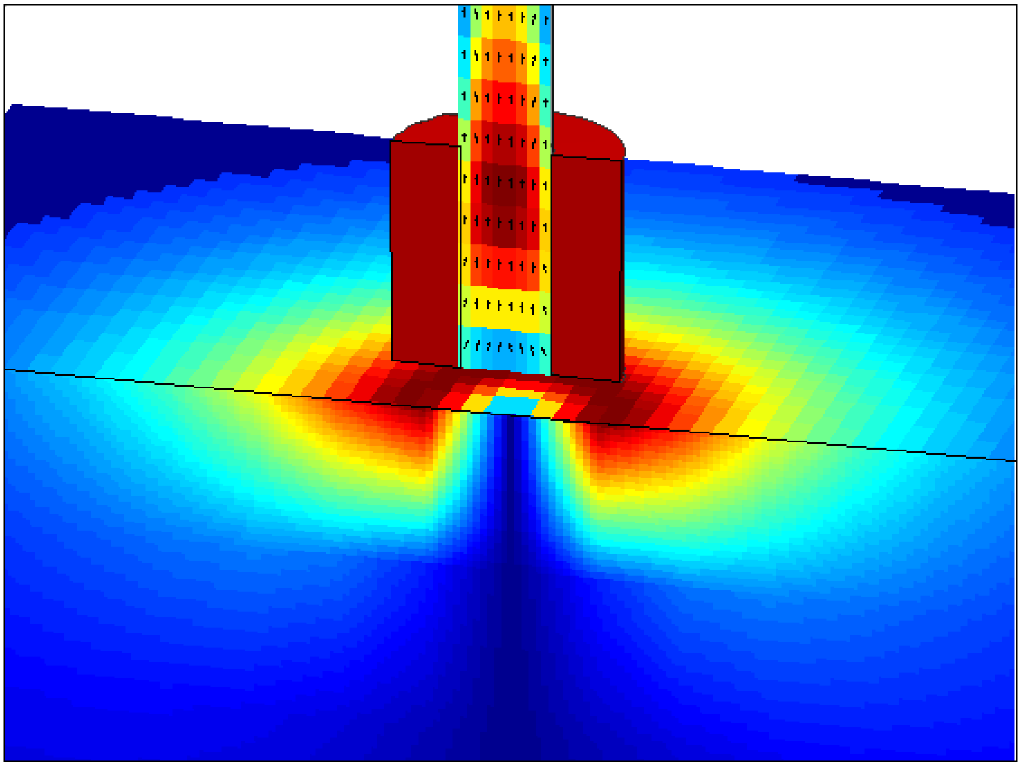


figure 6 : Eddy Currents below Probe 1 and flux density inside the ferrite core at 1 MHz

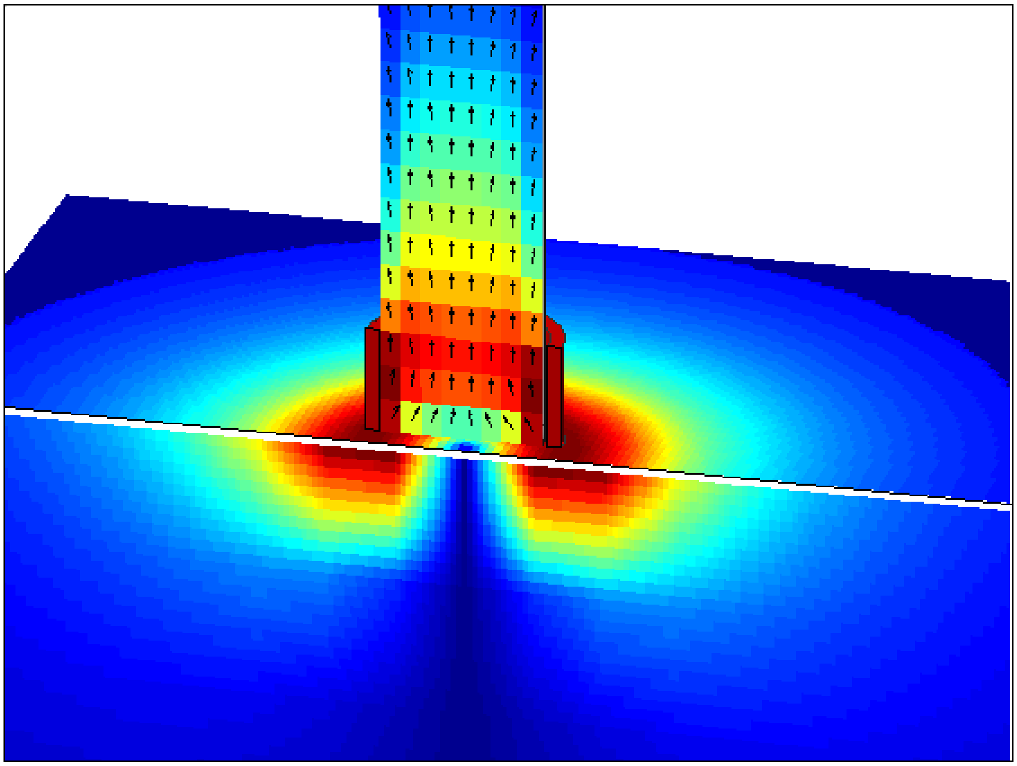


figure 7 : Eddy Currents below Probe 2 transmit coil and flux density inside the ferrite core at 100 kHz

Comparison between experimental data and simulation: The responses of Probe 1 and Probe 2 to rectangular notches of various lengths was computed and compared to experimental data. The notches have a depth of 1 mm, a width of 0.2 mm and a length ranging from 1 to 10 mm. The data are calibrated at 1 Volt and 0° for a notch of 20 mm long, 3 mm depth and 0.3 mm width. The cartography of the EC signal (real component) obtained for a 4 mm long notch is given in figure 8 for Probe 1 and in figure 9 for Probe 2. The X and Y-axis are orthonormal and one can clearly see a better resolution for Probe 1: the orientation and length of the notch is very well defined. The agreement between experimental data and simulation is excellent in amplitude and shape, and can also be observed in the impedance plane for the Lissajous pattern (figure 10 and figure 11).

Response of the probes versus the length of a notch: The variation of the EC signal amplitude is given in figure 12 for Probe 1 and in figure 13 for Probe 2. Regarding Probe 1, the EC amplitude rises steadily for a length varying from 1 mm to 5 mm and then levels off when the length is above 7 mm. Considering Probe 2, the response is slightly different from Probe 1. The variation of the magnitude with the length is nearly linear up to a length of 5 mm and then reaches a peak for a length of 6 ~7 mm corresponding to the distance between transmitter and receiver coils.

Discussion: Looking only on experimental data, it is difficult to see a difference between the responses of the two probes. This is largely due to the limited amount of data available and to the uncertainties affecting the measurement of the EC signals. Thus, the simulation of the response of EC probes is a powerful tool to perform a more accurate analysis of an inspection method. For example, the peak of the EC amplitude observed with Probe 2 for notches of length in the range of the transmitter/receiver distance can be significantly accentuated for deeper flaws. This effect is to be considered when an inspection procedure is based on a calibration on a set of artificial notches and when the detection criterion is defined by a threshold value.

Conclusions: The quantitative evaluation of the performances of an EC inspection method relies on the analysis of a number of signals obtained for various representative flaws. The use of a fast modeling tool is an efficient and a cost-effective way to produce such signals. The recent extension of the CIVA Eddy Current VIM code [2, 3, 4, 5] to ferrite-cored probes is meant to address those issues.

References:

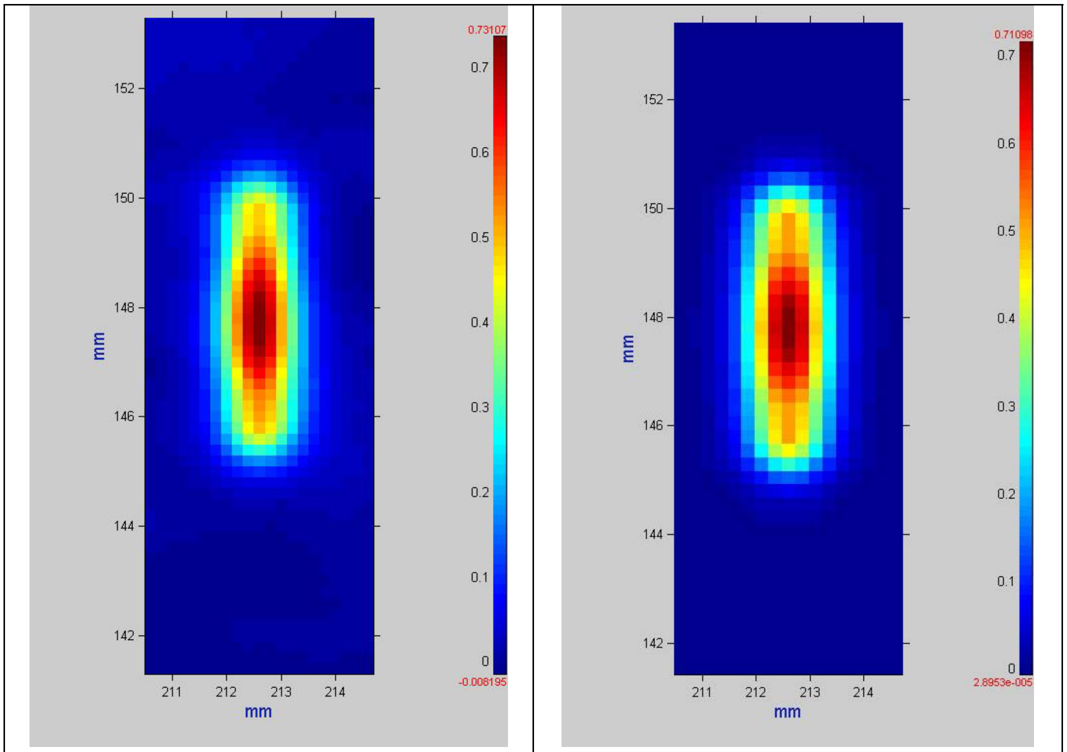
[1] Buvat, F., Pichenot, G., Lesselier, D., Lambert, M. and Voillaume, H., “A Fast Model of Eddy Current Ferrite-Cored Probes for NDE”, in ENDE’2003 Workshop Proceedings, IOS Press, 2004, pp. 44-51.

[2] Pichenot, G. and Sollier T., “Eddy current modelling for nondestructive testing”, Proc. 8th European Conf. On Nondestructive Testing, Barcelona, June 2002.

[3] Micolau, G., Pichenot, G., Lambert, M., Lesselier, D. and Prémel, D., “Three-Dimensional Electromagnetic Field in a Conductive Cylinder at Eddy-Current Frequencies”, in ENDE’2002 Workshop Proceedings.

[4] Micolau, G., Pichenot, G., Prémel, D., Lesselier, D., Lambert, M., “Dyad-Based Model of the Electric Field in a Conductive Cylinder at Eddy-Current Frequencies”, IEEE Trans. Magnetics Vol.40, No. 2, march 2004, pp. 400-409.

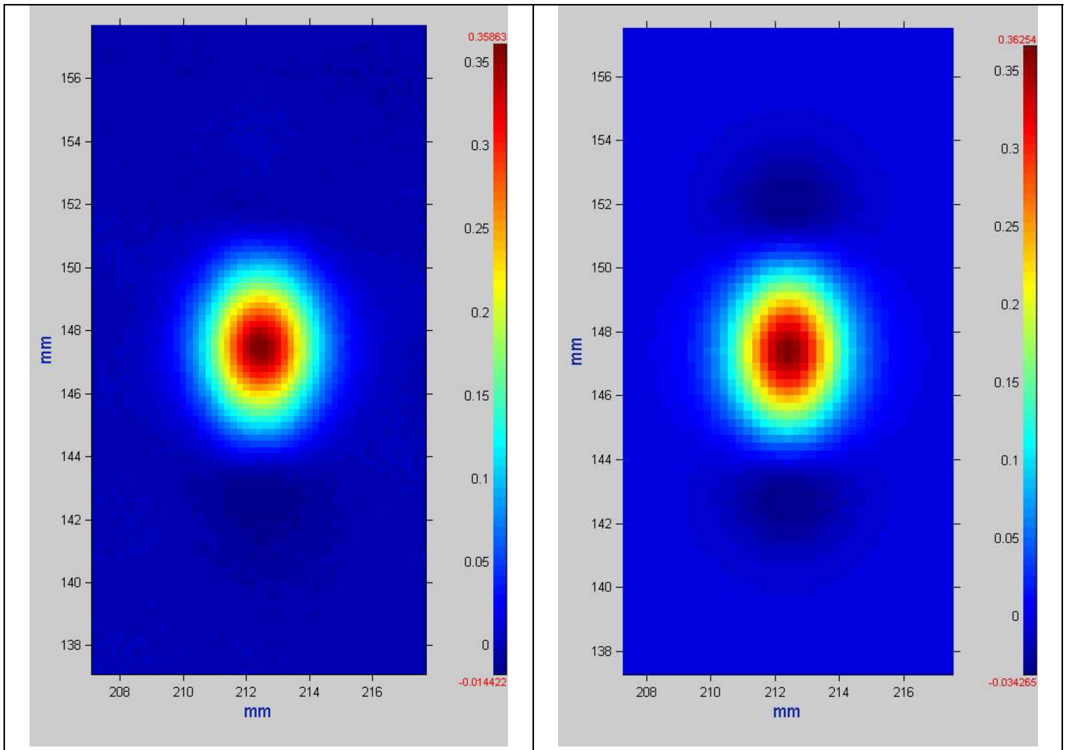
[5] Pichenot, G., Premel, D., Sollier T. and Maillot, V., “Development of a 3D Electromagnetic Model for Eddy Current Tubing Inspection: Application to Steam Generator Tubing”, in Review of Progress in QNDE Vol.23.



Experimental data

Simulation

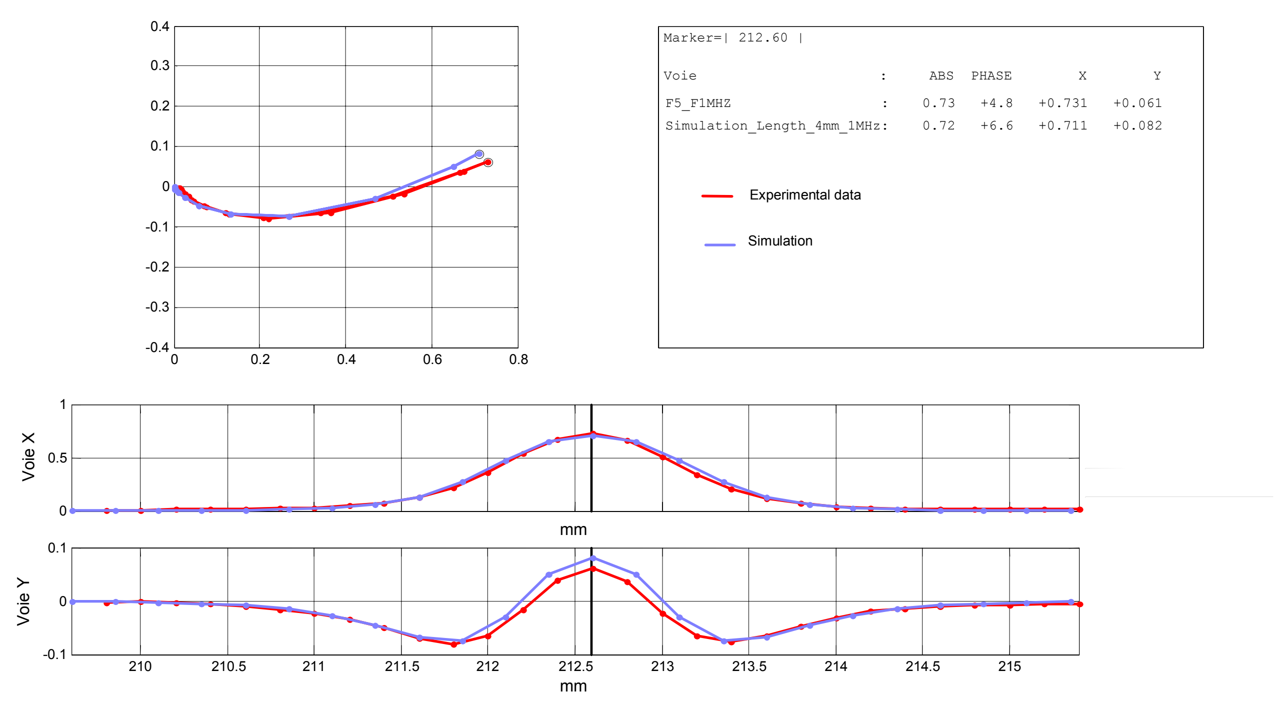
figure 8 : response of Probe 1 to a notch of length 4 mm, depth 1 mm and width 0.2 mm



Experimental data

Simulation

figure 9 : response of Probe 2 to a notch of length 4 mm, depth 1 mm and width 0.2 mm



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Marker=| 212.60 |

Voie                          :    ABS  PHASE        X         Y
F5_F1MHZ                      :    0.73   +4.8    +0.731    +0.061
Simulation_Length_4mm_1MHz:     0.72   +6.6    +0.711    +0.082
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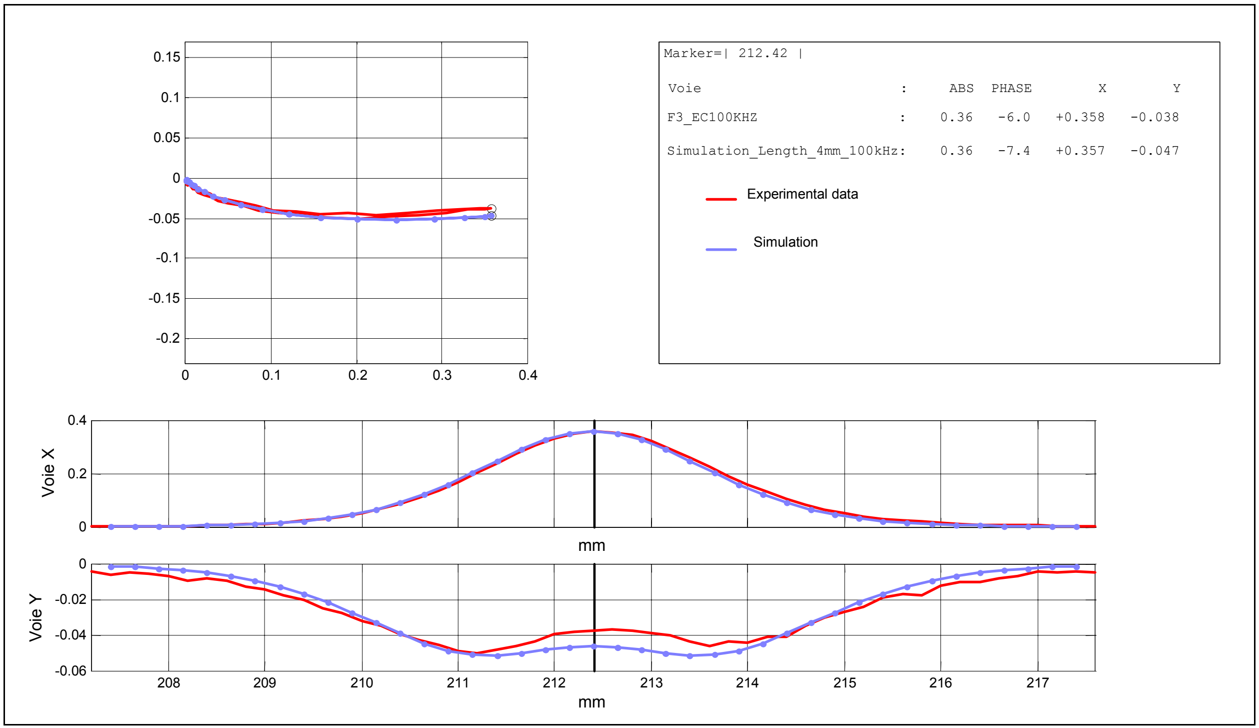
figure 10 : EC Lissajous of Probe 1 for a notch of length 4 mm, depth 1 mm and width 0.2 mm



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Voie                            :    ABS  PHASE       X         Y
F3_EC100KHZ                     :    0.36   -6.0   +0.358    -0.038
Simulation_Length_4mm_100kHz:    0.36   -7.4   +0.357    -0.047
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figure 11 : EC Lissajous of Probe 2 for a notch of length 4 mm, depth 1 mm and width 0.2 mm

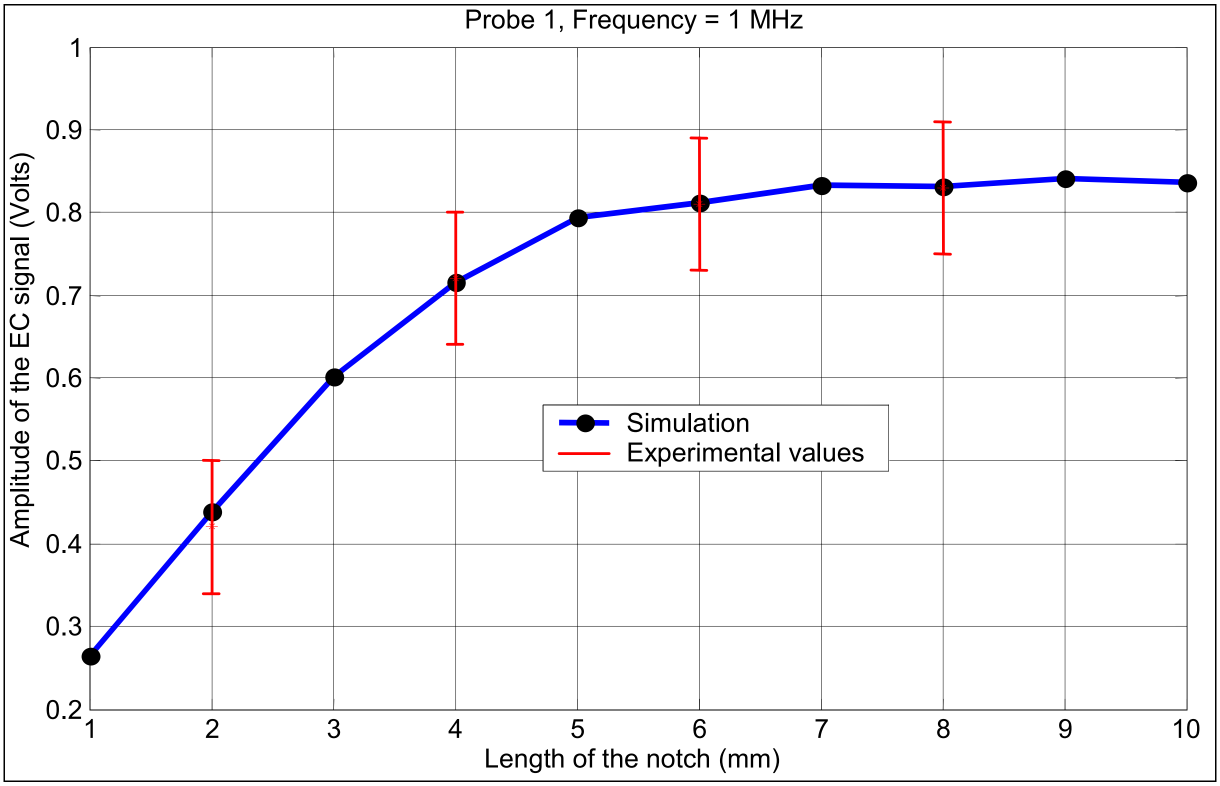

figure 12 : variation of the amplitude obtained with Probe 1 for a notch of depth 1 mm, width 0.2 mm

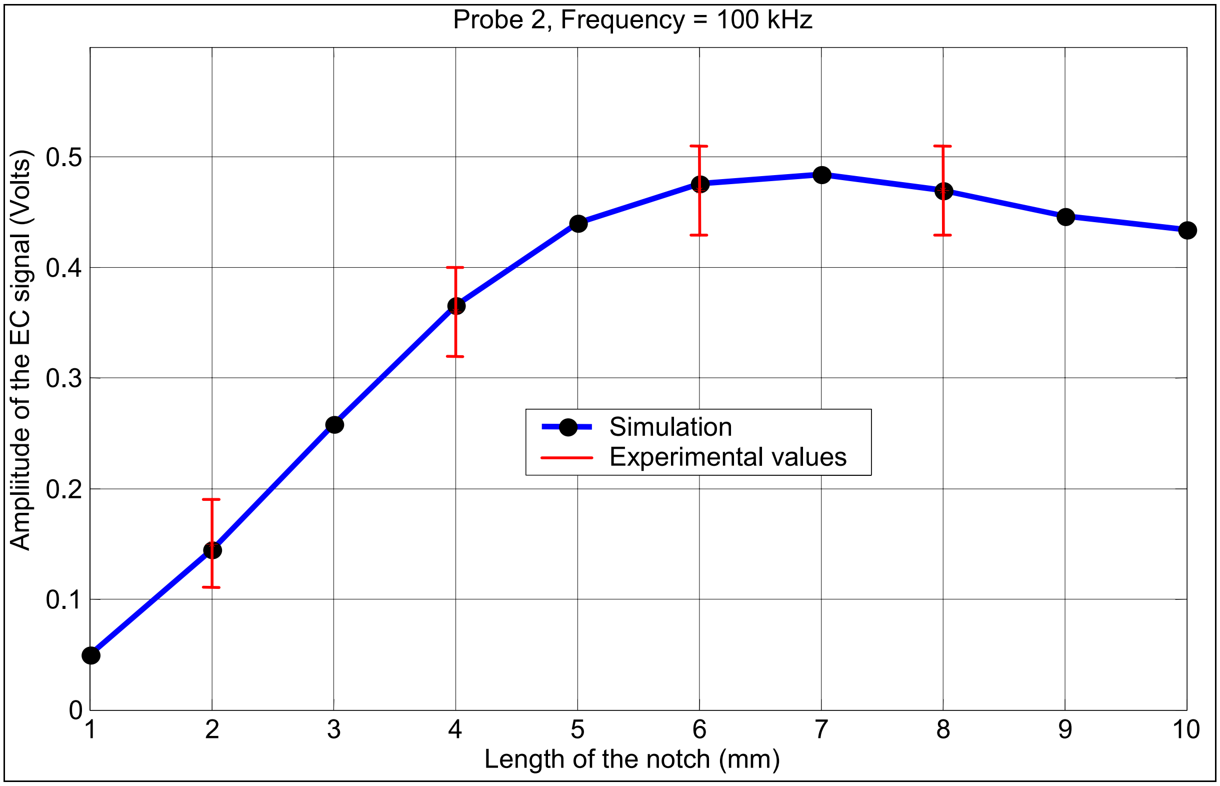

figure 13 : variation of the amplitude obtained with Probe 2 for a notch of depth 1 mm, width 0.2 mm