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Water channel thickness estimation through high frequency ultrasonic measurements

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ABSTRACT

As part of the conversion of the ILL fuel element to low-enriched uranium, a non-destructive PIE device has been developed to measure the swelling of the plates after irradiation. This device integrates two ultrasonic transducers inserted in a stainless-steel blade and resonating around 100 MHz. An ultrasonic wave propagates through the structure, producing series of acoustic echoes leading to the water channel thickness by a time-of-flight measurement. For the optimization of the device, it is necessary to understand the propagation behavior in the structure. We will present the latest Finite Different Time Domain simulation of the transducer-water channel-fuel plates system. The reflection of the ultrasonic waves on the fuel plate surfaces will be analyzed to estimate the channel thickness. Therefore, by simulating the propagation wave in the structure, we aim to analyze the physics of the generated echoes through the overall path.

1 Introduction

The Laue-Langevin Institute (ILL) has a High Flux Reactor (RHF) intended solely to fundamental research. It has a thermal power of 58 MW and produces the most intense continuous flux of neutrons in the world, about $1.5 * 10^{15}/cm^2/s$ [1]. The core of the RHF is composed of a single cylindrical fuel element made of 280 curved plates machined in involute shape to ensure a nominal inter-plate distance of 1.8 mm. This fuel element is immersed in a cooling pool at a depth of 12 m to ensure protection against gamma and neutron radiation.

During irradiation, structural modifications may appear on the surface of the fuel plates bearing information on the irradiation history, in particular the swelling of the fuel plates. As part of its conversion to a low-enriched fuel, the ILL wishes to develop a non-destructive device to evaluate and characterize the structural modifications of the plates at the microscopic scale: namely, the characterization of the thickness of the water channel separating two fuel plates.

In a previous work [2-4], two ultrasonic devices combining mechanics, electronics and acoustics have been designed. They are intended to be introduced into an interval close to 1.8 mm separating two plates. They are based on two ultrasonic transducers resonating on high frequencies inserted in a stainless-steel blade, which is 1 mm thick respecting nuclear quality standards. The surface estimation is based on the Pulse-Echo method which consists in measuring the time of flight (ToF) [5] of the signal reflected on the fuel plate. Considering the ultrasonic velocity c of water, the distance d corresponding to the elapsed time between the emission of the wave and its reception is evaluated by:

$$d = \frac{c * t}{2} \,. \tag{1}$$

The results obtained during the in-situ measurements between the plates of the RHF at the ILL confirmed the feasibility of the measurements (see Fig. 1). The ultrasonic devices developed showed a good behavior under irradiation [6].

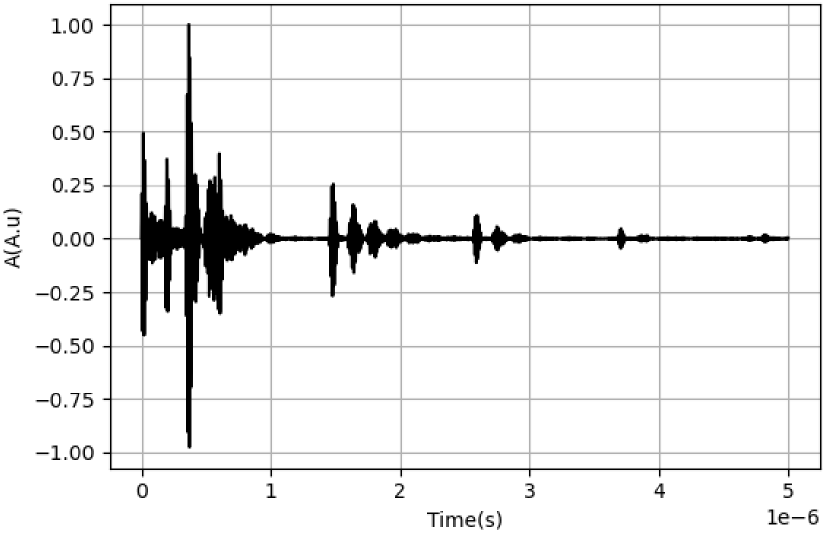


Figure 1 : Experimental signal revealing the two series of echoes.

To study the spatial and temporal nature of the acoustic field, a numerical wave simulation presents a very important tool to understand its propagation. The Finite Difference Time Domain (FDTD) method allows the study of both temporal and spatial behavior of the acoustic field in the complex structure of the transducers as well as in the propagation environment. The following sections will present the model and its application to the modeling of the device behavior.

2 Measuring principle

The ultrasonic transducers manufactured in the laboratory are machined on a blade to be introduced into the inter-plate distance (Fig 3). They send and receive ultrasonic waves that relay back information about the inter-plate distance. The device allows the determination of the distance to a fuel plate by measuring the time interval between sending and receiving the ultrasonic pulse. To have a good signal-to-noise ratio, the centering of the ultrasonic device into the water channel is critical for the measurement. Consequently, the misalignment of the transducers impacts the quality of the signals received, which leads to inaccuracy in the measurement of the time-of-flight measurement. A numerical study to simulate the interaction of the ultrasonic waves at each point of the structure is necessary to estimate the behavior of the acoustic field.

3 FDTD method

1.1 Principle of the method

Finite Difference Time Domain (FDTD) is a method developed by Kane Yee [7] in 1966 to study problems in electromagnetism, and which was subsequently applied in many scientific fields such as acoustics [8]. In the context of modeling the wave propagation equation, the FDTD method is mainly characterized by a finite difference approximation of the spatial and temporal derivatives of the pressure and displacement vectors [9] of the acoustic field. The equations of motion describing the propagation of elastic waves in a two-dimensional medium are described by the following differential equations:

$$\frac{\partial v_x(x,z,t)}{\partial t} = \frac{1}{\rho}\frac{\partial p(x,z,t)}{\partial x}, \tag{2}$$

$$\frac{\partial v_z(x,z,t)}{\partial t} = \frac{1}{\rho}\frac{\partial p(x,z,t)}{\partial z}, \tag{3}$$

$$\frac{\partial p(x,z,t)}{\partial t} = E(x)\left(\frac{\partial v_x(x,z,t)}{\partial x} + \frac{\partial v_z(x,z,t)}{\partial z}\right). \tag{4}$$

Here $v_x\ and\ v_z$ represent the particles of the velocity vector on the coordinates x and z, p the acoustic pressure, ρ the material density and E the young's modulus.

The spatial and temporal derivatives of each function f can be represented by $\partial f\ /\ \partial x$, $\partial f\ /\ \partial z\ and\ \partial f\ /\ \partial t$ and approximated by a central finite differences $(f(x+\Delta x/2)-f(x-\Delta x/2))/\Delta x,\ (f(z+\Delta z/2)-f(x-\Delta z/2))/\Delta z\ and\ (f(t+\Delta t/2)-f(t-\Delta t/2))/\Delta t.$

The discrete system is presented in the following equations where n, i and j represent respectively the time and the space indices:

$$vx^{n+1}_{i+1/2,j} - vx^{n}_{i+\frac{1}{2},j} = \frac{\Delta t}{\rho * h}\left(p^{n}_{i+1,j} - p^{n}_{i,j}\right), \tag{5}$$

$$vz^{n+\frac{1}{2}}_{i,j+\frac{1}{2}} - vz^{n-\frac{1}{2}}_{i,j+\frac{1}{2}} = \frac{\Delta t}{\rho * h}\left(p^{n}_{i,j+1} - p^{n}_{i,j}\right), \tag{6}$$

$$\begin{aligned} p^{n+1}_{i,j} - p^{n}_{i,j} = \frac{\Delta t * E_{i,j}}{h}\Big(&vx^{n+\frac{1}{2}}_{i+\frac{1}{2},j} - vx^{n+\frac{1}{2}}_{i-\frac{1}{2},j} \\ &+ vz^{n+\frac{1}{2}}_{i,j+\frac{1}{2}} - vz^{n+\frac{1}{2}}_{i,j-\frac{1}{2}}\Big). \end{aligned} \tag{7}$$

In this study, the accuracy of the calculation depends mainly on the choice of the sampling step of the modeled structure. Therefore, the discretization of the grid must verify the stability condition to ensure better convergence of the results. The Courant Friedrich Lewy (CFL) stability criterion [10] relies on the relation of two velocities: the physical velocity of the wave propagation in the medium and the grid velocity which is the grid increment dx divided by the time increment dt.

In this study, we have discretized our model into a rectangular mesh which consists of loading the acoustic pressure at points i and j respectively along the x and z-axis in the calculation grid and the acoustic velocity at points (i-1/2) along the x-axis and (j-1/2) along the z-axis. The numerical scheme of the calculation is presented in figure 2.

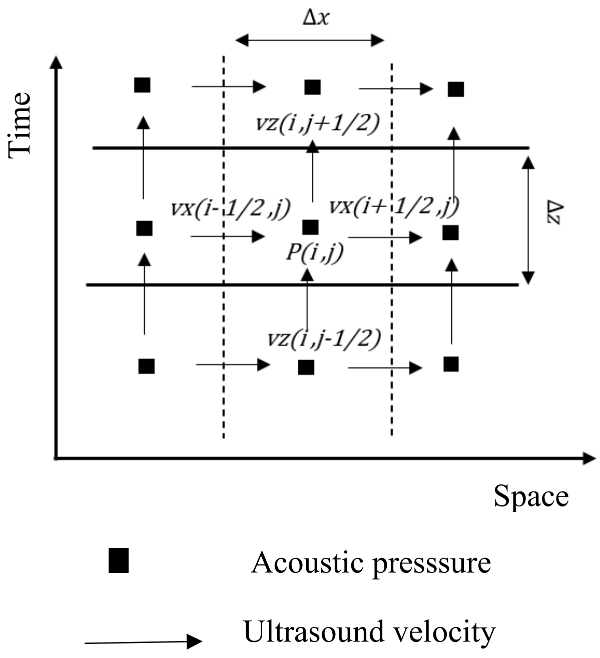


Figure 2: Geometry of the scheme on shifted grids for two-dimensional system.

At t=0, the pressure and the ultrasonic velocities applied to the system are in equilibrium and they are set to zero throughout the calculation grid.

1.2 FDTD SCHEME

The illustration of the figure 3 shows the structure of two ultrasonic transducers composed of a piezoelectric element (LiNbO3) thinned to 40 µm and resonating at a frequency of 100 MHz. Then, they are bonded to a silica delay line of 400 µm with a density of $\rho_{Sio2} = 2100\ kg.m^{-3}$ and a longitudinal velocity of $c_{Sio2} = 5837\ m.s^{-1}$.

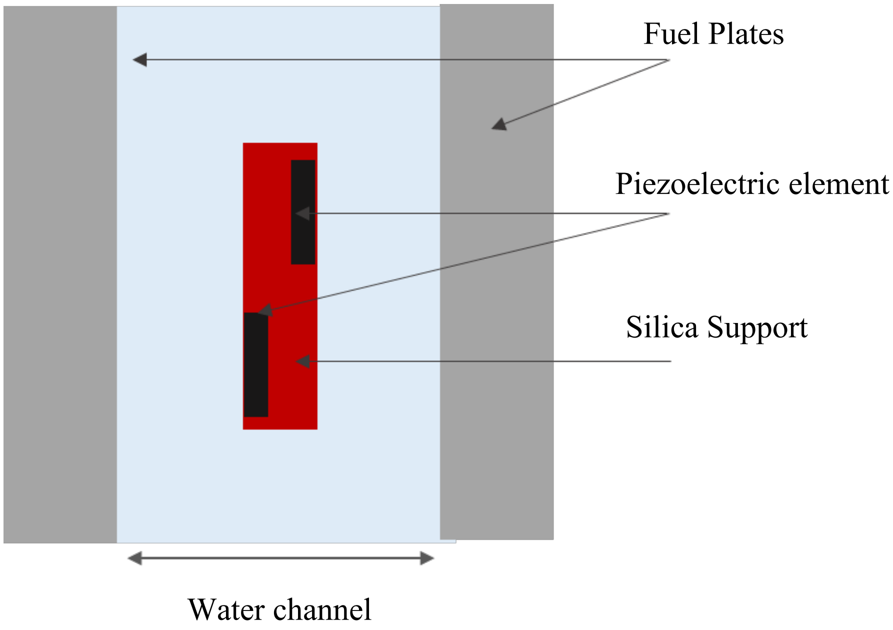


Figure 3: Illustration of the measurement system

The transducers are placed in a water channel separating two fuel plates with a density of $\rho_w = 1000\ kg.m^{-3}$ and a longitudinal velocity of $c_w = 1490\ m.s^{-1}$. In all the following simulations, an 100 MHz initial pressure pulse will be applied to the two transducers of the system in the grid through a sinusoidal burst modulated by a Gaussian represented in figure 4.

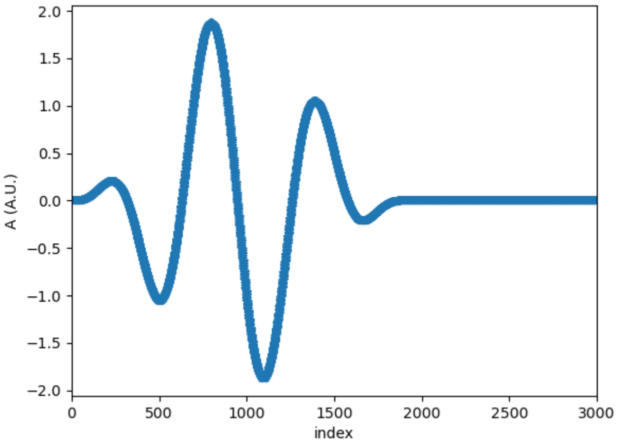
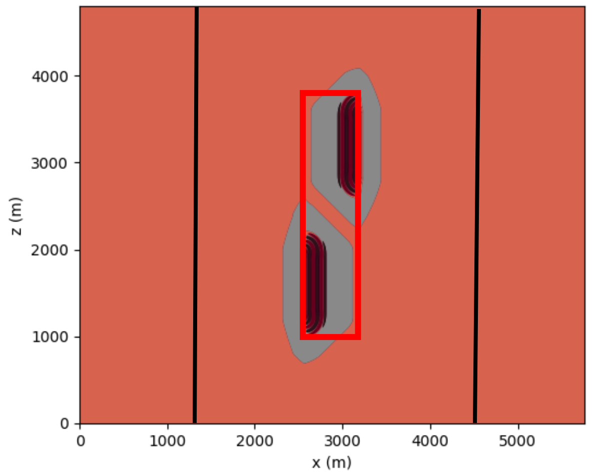


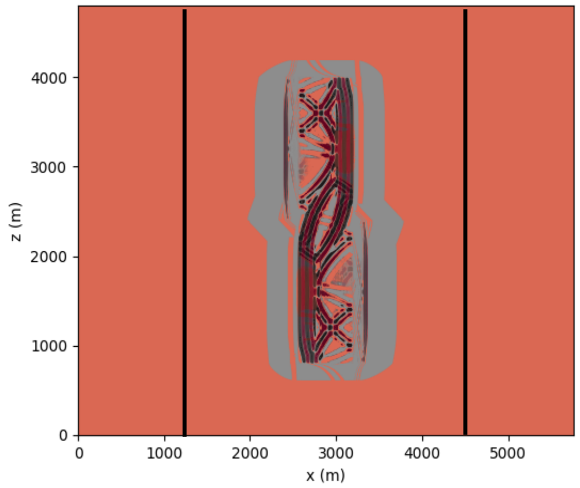
Figure 4: Initial excitation pulse applied to the two ultrasonic transducers

1.3 Simulation and Results

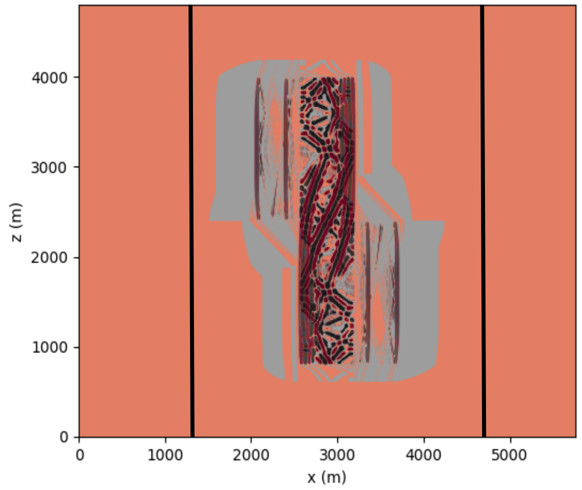
The figure 5 shows snapshots of the wave propagation in the structure modeled. Firstly, after the application of the source excitation to each element piezoelectric, the wave propagates in the silica delay line producing a first series of echoes (Fig 5.a and b). Then, it propagates through the water channel until the fuel plates (Fig 5.c and d). The wave bounces back to the sensor and the 2nd series of echoes occurs (Fig 5.e).



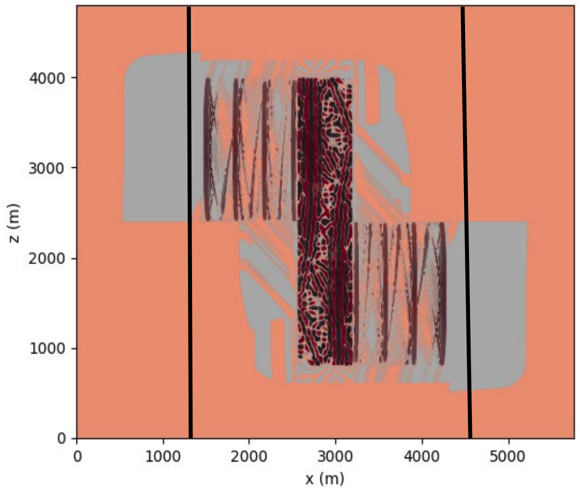
(a)



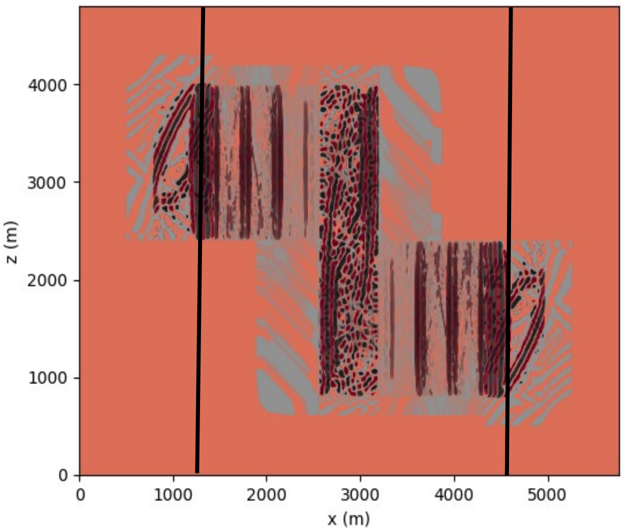
(b)



(c)



(d)



(e)

Figure 5: Representation of the evolution of ultrasonic wave propagation in the bi-sensor structure

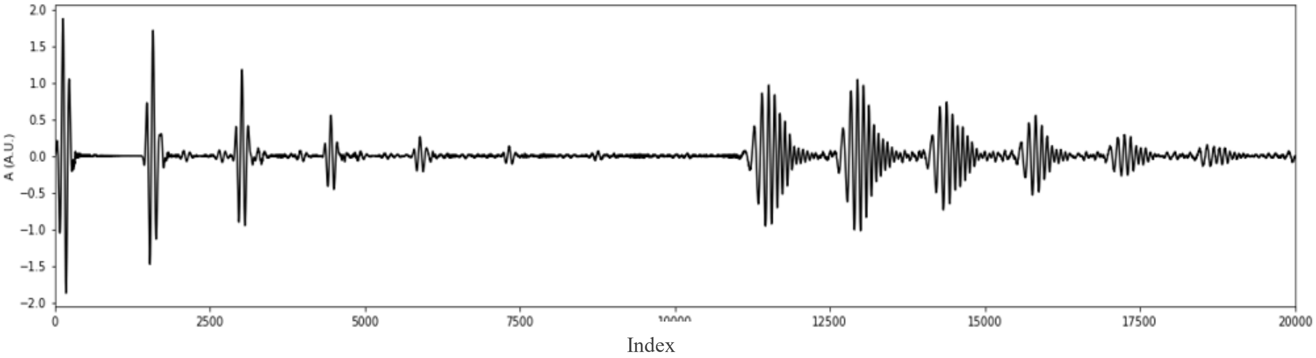


Figure 6: Modeled ultrasonic signal at 100 MHz showing two series of echoes

The result of the simulation is shown in Fig. 6, where the reflection of the initial pulse (Fig 4) on the boundaries of the silica support and the fuel plates with different ultrasound velocities are presented in two series of echoes.

This implementation gives us information about different communication occurring between the two piezoelectric elements, especially the interaction shown in (Fig 5.b). This latter corresponds to the crosstalk phenomena for which the effect is represented by additional echoes appearing between the first series of echoes in (Fig 6). This phenomenon may be a result of two major factors: the first one consists of the electrical crosstalk due to the capacitive effect between the two piezoelectric elements of the transducer. And the second one is assumed to be a mechanical crosstalk which generated by the different modes of vibrations of the piezoelectric elements [11-12].

4 Conclusion

To summarize, in this paper, a study of FDTD scheme for the comprehension of the propagation of the ultrasonic waves in a 2D problems have been analyzed.

We have focused on the differential equations and a simulation of the propagation of the acoustic field of two transducers bonded to a silica support and intended to be introduced into a nominal distance separating two fuel plates.

This method is a visualization technique that contributes to analyze the interaction into the boundaries of the reflection of ultrasonic waves propagating in complex media.

Further work may lead to optimize the performance of the ultrasonic element by the reduction of crosstalk showed on the results obtained for an accurate acquired signal. This will allow us to evaluate with high precision influence of the transducer behavior on the measurement of the inter plate distance during the next in situ measurement inside the high flux reactor.

5 Acknowledgements

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6 References

[1] www.ill.eu.

[2] G. Zaz, Y. Calzavara, E. Le Clézio, et G. Despaux, « Adaptation of a High Frequency Ultrasonic Transducer to the Measurement of Water Temperature in a Nuclear Reactor », Physics Procedia, vol. 70, p. 195-198, janv. 2015, doi: 10.1016/j.phpro.2015.08.116.

[3] G. Zaz, A. Dekkious, P. A. Meignen, Y. Calzavara, E. Le Clézio, et G. Despaux, « High Frequency Transducer Dedicated to the High-resolution in Situ Measurement of the Distance between Two Nuclear Fuel Plates », Physics Procedia, vol. 70, p. 191-194, janv. 2015, doi: 10.1016/j.phpro.2015.08.110.

[4] G. Zaz, E. Le Clézio, A. Dekious, M. C. Alaoui, Y. Calzavara, et G. Despaux, « In-Situ High-Resolution Measurement of HFR Nuclear Fuel Plates' Spacing », IEEE Transactions on Nuclear Science, vol. 65, nº 11, p. 2776-2783, nov. 2018, doi: 10.1109/TNS.2018.2875310.

[5] D. Marioli, E. Sardini and A. Taroni, "Ultrasonic Distance Measurement for Linear and Angular Position Control." IEEE Transactions on instrumentation and measurement, 37, December 1988.

[6] M.C. Alaoui, "High Frequency Ultrasonic Device development for Non-Destructive Post Irradiation Examination of the RHF Fuel Element.". Université Montpellier, 2018.

[7] K.Yee. "Numerical solution of initial boundary value problems involving maxwell's equations in isotropic media". IEEE Transactions on Antennas and Propagation, 302–307, 1966.

[8] S. Wang, “Finite-difference time-domain approach to underwater acoustic scattering problems”, J Acoust Soc Am, 1924 - 1931, 1996

[9] J.Vireux, P-SV wave propagation in heterogeneous media: velocity-stress finite-difference method , J Acoust Soc Am, vol. 104, no 5, p. 2604 -2014, 1998.

[10] R. Courant, K. Friedrichs, and H. Lewy. “On the Partial Difference Equations of Mathematical Physics.” IBM Journal of Research and Development, 11(2) :215–234, March 1967

[11] Friedrich W, Kaarmann H, Lerch R. “Finite element modeling of acoustic radiation from piezoelectric phased array antennas”.IEEE Ultrasonics Symposium: Proceedings of the IEEE Ultrasonics Symposium, 1990 Dec 4-7; Honolulu, USA. Honolulu; 1990.

[12] Gori P, Iula A, Pappalardo M, Lamberti N, Montero de Espinosa F. “Influence of the inter-element coupling on ultrasound array radiation patterns”. Journal of Computational Acoustics. 2001