# WATER CHANNEL THICKNESS ESTIMATION THROUGH HIGH FREQUENCY ULTRASONIC MEASUREMENT

**Rhofrane Mrabti*** **Emmanuel Le Clézio**[1] **Yoann Calzavara**[2]
**Gilles Despaux**[1]

[1] IES, University of Montpellier, CNRS, 34000 Montpellier, France
[2] Laue Langevin Institute, 71 rue des Martyrs, 38000 Grenoble, France.

## ABSTRACT

The conversion of the highly enriched fuel element of the ILL into a low-enriched fuel element implies the development of new investigation tools to evaluate the inter-plate distance. Originally of 1.8 mm, this characteristic is impacted during the reactor life cycle by a swelling phenomenon of the fuel plates. In this context, a high-frequency ultrasonic device is developed to be introduced into the water channel separating two fuel plates. It should allow a non-destructive investigation of the element history of irradiation. The device integrates two ultrasonic transducers resonating at frequencies around 100 MHz and is machined at the end of a 1 mm thick inox blade. These transducers are coupled to an electronic system for the emission and acquisition of the ultrasonic signals propagating in the water-channel structure.

In this paper, the results of the simulation of the propagation field in the structure will be considered using the Finite Element method (FEM). It will focus especially on the interaction of the acoustic wave with the medium of the propagation.

**Keywords:** *High Frequency, Ultrasound transducer, finite element analysis, RHF.*

## 1. INTRODUCTION

In the framework of minimizing the nuclear proliferation risks, most of the High-Performance Research Reactors (HPRR) are intensely involved in converting their fuel elements into low Enriched Uranium (LEU). They are currently using a plate dispersed in a pure Aluminum matrix. The conversion program requires the use of Low-Enriched Uranium (LEU) with minimal losses and achieving similar performance as High-Enriched Uranium (HEU) [1].

The High Flux Reactor (RHF) of the Institute Laue Langevin (ILL) has launched a collaboration with the Institute of Electronics and Systems (IES) of Montpellier University (UM) to investigate in a non-destructive way the fuel behavior and the history of irradiation to improve its qualification.

The ILL operates a High Flux Reactor (RHF) dedicated only to fundamental research; it has a thermal power of 58 MW and produces the most intense continuous flux of neutrons in the world, with a flux density of approximately 1.5.1015/cm2/ s [2].

The core of the RHF is mainly composed of 280 curved fuel plates, machined in an involute shape to ensure the nominal inter-plate distance of 1.8mm.

To maintain the reactor at a safe operating temperature after the radiation cycle, the fuel element is immersed in a cooling pool at a depth of 12 meters, which also helps to ensure safety against gamma and neutron radiation, which are produced during the cycle of the reactor.

The main objective of this research project is to develop a high-frequency ultrasonic device that combines mechanics, electronics, and acoustics for non-destructive in-situ measurement of the fuel plate with a micrometric resolution. The specific device integrates two ultrasonic transducers for measuring the water channel width between two fuel plates of the HPRR.

In previous studies [2-3], two specific ultrasonic devices have been designed to measure the inter-plate distance of the HPRR spent fuel element with a microscopic resolution. They are intended to be introduced into the gap of 1.8 mm

---

****Corresponding author***: *rhofrane.mrabti@ies.univ-montp2.fr* between two fuel plates. The feasibility of this measurement has already been demonstrated during a series of experiments conducted in December 2013 and July 2015, where the different components of the ultrasonic device showed good resistance to radiation, and the experimental difficulties and constraints associated with the measurement were identified.

The next step in the project aims to improve the measurement accuracy by optimizing the ultrasonic device considering the limitations associated with the measurement. The objective is to obtain the radiation history and feedback on the whole set of plates of the ILL spent fuel elements.

After representing the ultrasonic device used for such measurement, this paper will describe a Finite Element Modelling using the commercial software COMSOL Multiphysics for a simulation of the ultrasonic wave propagation within the transducers. The objective is to understand the physics of wave behavior within the transducer's structure.

## 2. ULTRASONIC DEVICE PRINCPLE

The measurement principle is based on two transducers composed of two piezoelectric elements bonded on both faces of unique silica support and mounted on one end of a 1 mm thick, 10 mm wide, and 1500 mm long inox blade. After the blade introduction in the water channel, the inter-plate distance measurement is based on the general principle presented in Figure 1. The excitation of the two piezoelectric elements is ensured by two semi-rigid coax cables connected to an electrode. They are connected to a 20 m cable to allow the emission and reception of the ultrasonic wave at very high frequencies by a dual transmitter/receiver electronic system designed to ensure the excitation signal of the two transducers.

After the generation of the ultrasonic wave, the first series of echoes corresponds to the multi-reflection of the initial wave on the silica support, and the second corresponds to the multi-reflection on the fuel plates, as described in Figure 2. Here, the pulse-echo method is used to quantify the time of flight between the first reflection on the silica support and the first reflection on the fuel plate. Regarding the ultrasonic velocity in the medium of the propagation, the distance inter-plate is evaluated by:

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

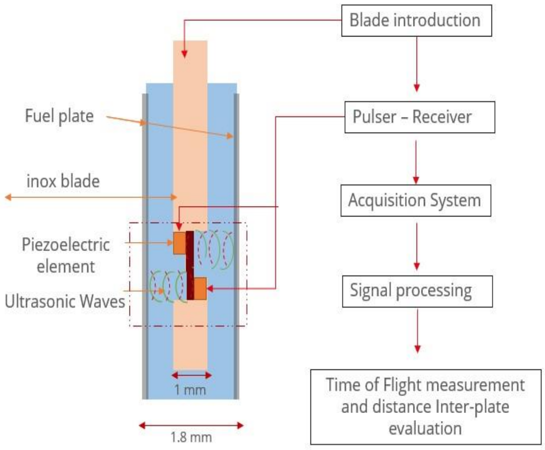

**Figure 1**. Illustration of the measurement system.

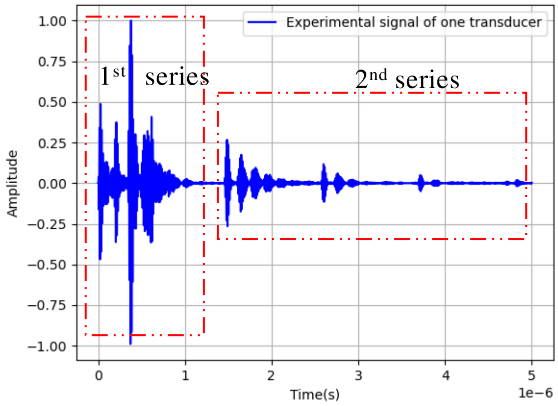

**Figure 2**. Experimental signal revealing two series of echoes.

This paper aims to simulate the wave propagation in the time domain with the Finite Element Method (FEM) in the silica support to understand the complex structure of the composite reflected signal, as described in Figure 3.

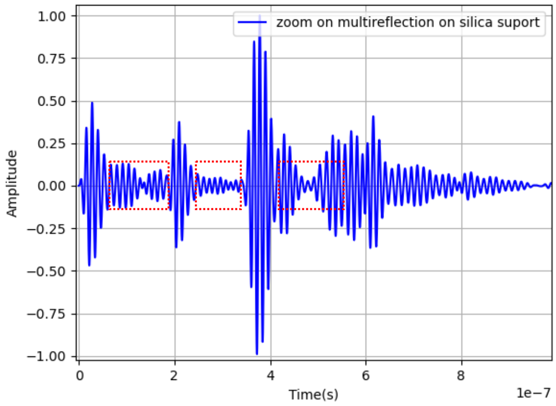

**Figure 3**. Zoom on the first series of echoes of the simulated signal.

## 3. FEM MODELING

COMSOL Multiphysics is a commercial simulation software allowing users to design, simulate and analyze complex structures and models with various coupled physics. It is mainly based on finite element analysis for solving partial differential equations associated with the physics of the studied design. In this context, we have used the Acoustics Module in COMSOL to model, generate and simulate the propagation of the ultrasonic waves in the transducers to understand the different interactions between the transducers and the silica support.

## 4. MODEL DEVELOPEMENT

In this paper, we present a simplified 2D model to simulate the propagation of the acoustic wave through the silica support with different acoustics parameters involving the definition of the various structures of the geometry and defining the materials, as well as specifying the boundary conditions and the source of the acoustic waves.
The ultrasonic device has been modeled using a 2D pressure Acoustics model. The simulation describes the pressure field during non-destructive testing based on a pulse-echo technique, in which the transducers react as transmitters and receivers of the ultrasonic wave.
The following equation governs the pressure acoustics distribution:

$$\frac{1}{\rho c^2}\frac{\partial^2 p}{\partial t^2} - \frac{1}{\rho_0}\nabla^2 p = 0 \tag{2}$$

where c, p, and ρ represent, respectively, the ultrasound velocity of the medium, the ultrasound wave pressure, and the material density.

As presented in Figure 4, the ultrasonic device has been modeled using a 2D Pressure Acoustics model. The ultrasonic transducers are shown as a rectangle of 400 µm in height and 6mm in width, representing the silica support and two lines of sources of 1 mm in length.

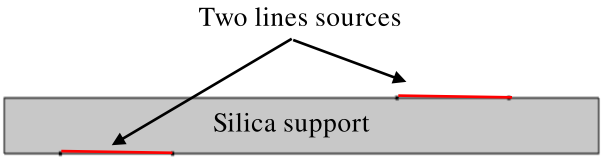

**Figure 4**. 2D geometry model of the FEM.

### 4.1 Material and ultrasonic waves properties

In the laboratory, the transducers mainly comprise a piezoelectric element bonded to a specific support. In our study, the model neglects the presence of the piezoelectric element within the structure of the transducers, and Silica Glass was considered as the definite material with the following characteristics that are important for the representation of the acoustic wave: its density, Young's modulus, Poisson's ratio, and acoustic velocity. These properties are described below in Table 1.

**Table 1.** Characteristics used for the FEM of the transducers.

| Material properties | Numeric value | Unit |
|---|---|---|
| Density | 2200 | Kg/m^3 |
| Young's Modulus | 73 | GPa |
| Poisson's ratio | 0.17 | -- |
| Acoustic velocity | 5331 | m/s |

The input pressure signal in Figure 5 is modeled as a line source in the model and represented as a sinusoidal wave modulated by a Gaussian envelope with a central frequency of 100 MHz.

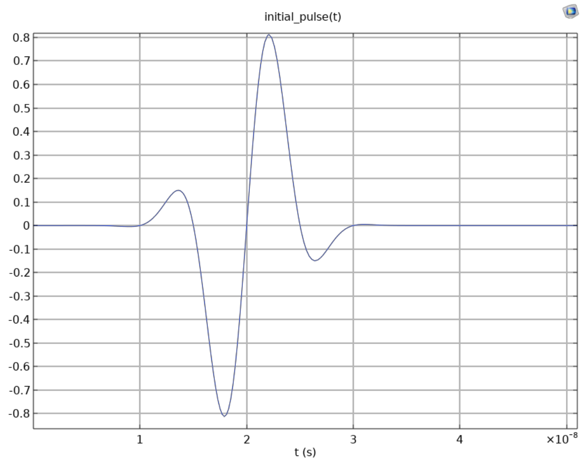

**Figure 5**. Time domain signal of the initial excitation pulse applied to the two lines sources.

## 4.2 Meshing

The meshing in the model is generated with a triangular element using the free meshing option in COMSOL. The maximum and the minimum element size is determined by the following equation $\Delta x = \lambda/5$, where $\lambda$ corresponds to the wavelength of the longitudinal wave in the silica glass.
The Courant-Friedrichs-Lewy criterion [5] is used to ensure the solution's accuracy and stability in the simulation's time-dependent solver. It is defined by $\Delta x/c$ in the FEM model, where c represents the longitudinal ultrasound velocity of the propagation medium.
Based on the velocity of the silica glass and the maximum element size in model $\Delta x$, the critical time step is calculated and defined as 1.98*10-7 seconds.

## 5. RESULTS OF THE SIMULATION

The following time lapses snapshots in Figure 6 show the simulation of the pressure distribution of the wave at different times. In Fig. 6a, the initial pulse of Figure 5. has just been generated by the two lines sources of the model and is propagating in the silica support as shown in Fig. 6b, Fig. 6c, the waves reflect on the boundary of the silica support and bounce back to the sources. The model has a series of reflections between the sources and the interface. In Fig. 6f and Fig. 6g, communication between the two sources is observed due to the wave propagation in the structure.

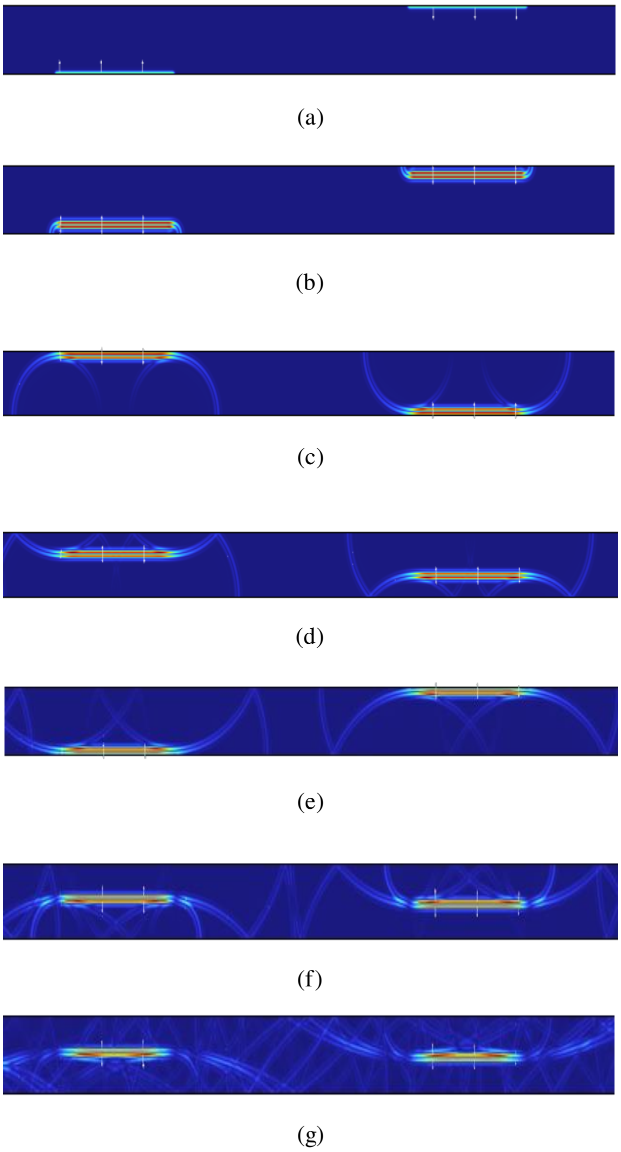
(a)
(b)
(c)
(d)
(e)
(f)
(g)

**Figure 6.** Simulation of ultrasonic pressure field in the silica support at times.

The received simulated signals in the time domain are presented in Figure 7 and Figure 8. As previously mentioned, the transducers acted as transmitters and receivers of the acoustic waves based on the pulse-echo technique. Those temporal signals represent the multiple reflections along the 400 µm of the silica support. They are relatively separated by a specific Time of Flight (ToF) of about 0.15 µs which corresponds to the time taken by the wave to travel through the surface of the support.

Moreover, the interaction shown in Fig. 6g between the two-line sources is represented in the temporal signal through the additional echoes shown in Figures 7 and 8 in the red rectangle between the multiple reflections. This communication can be explained by a mechanical crosstalk phenomenon produced by different modes of vibrations of sources [11-12].

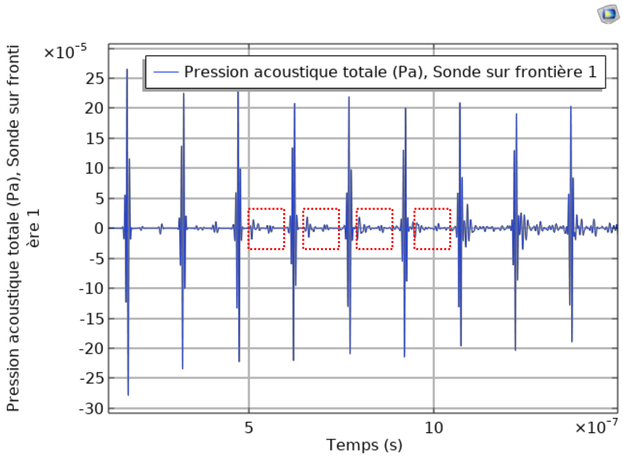

**Figure 7.** Temporal signal of the multireflection of the first line source.

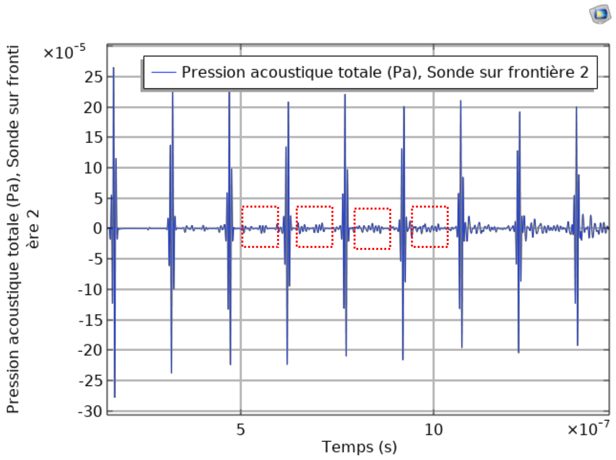

**Figure 8**. Temporal signal of the multireflection of the second line source.

## 6. CONCLUSION

In this paper, a finite element model (FEM) of an ultrasonic transducer for non-destructive testing has been developed using the Acoustics Modules of COMSOL Multiphysics. We focused on the description of the pressure distribution in the structure for a better comprehension of the ultrasonic wave behavior. The studied geometry describes a simple time domain simulation with two-line sources and backing support for an ultrasound transducer representation.
This simulation leads to optimizing the performance of the ultrasonic element by implementing a specific signal processing to optimize the performance of the ultrasonic device for an accurate measurement.
Further work will also extend this study and focus on modeling a more complex geometry, including the propagation field's multilayered structure. We will also generate waves to be concentrated within the depth of the fuel plates.

## 7. ACKNOWLEDGMENTS

The authors would like to thank Y. Launay, O. Guillemard, and A. Fournier for their strong contribution to manufacturing the ultrasonic device and the associated mechanical bench and electronics.

## 8. REFERENCES

[1] The HERACLES Working Group CEA, AREVA-CERCA, ILL, SCK-CEN, TUM. Heracles-cp: Towards the conversion of high performance research reactors in Europe. 2014.

[2] www.ill.eu.

[3] Zaz, G., Dekkious, A., Meignen, P. A., Calzavara, Y., Le Clézio, E., & Despaux, G. (2015). ‘’High frequency transducer dedicated to the high-resolution in situ measurement of the distance between two nuclear fuel plates,’’ in Proc. Physics Procedia, 70, 191-194.

[4] Alaoui, M. C., Zaz, G., Calzavara, Y., Le Clézio, E., & Despaux, G, “Caractérisation ultrasonore hautes fréquences de la distance inter-plaques au sein de réacteurs RHF in Proc. *Of* 7ème Colloque Interdisciplinaire en Instrumentation. January,2016.

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