Effect of turbulence on ultrasound propagation for vibration measurements of PWR assemblies in the HERMES P loop of the POSEIDON platform.

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Abstract— **This study focuses on the propagation of ultrasonic waves through a turbulent water flow representative of the hydraulic environment near a mixing grid in a Pressurized Water Reactor (PWR). Ultrasonic measurement, which relies on accurate knowledge of the acoustic velocity, is an effective non-intrusive technique for detecting displacements under harsh conditions. However, in turbulent flows, local velocity fluctuations induced by vortices can disrupt wave propagation, leading to measurement dispersion.**

An experimental setup was implemented to quantify these effects by comparing ultrasonic time-of-flight fluctuations upstream and downstream of a vortex-generating obstacle. The 1σ standard deviation from multiple acquisitions was used to characterize the variability of the measurements. The results show that dispersion increases with vortex density, but remains below 15 µm even in the most turbulent regions. In contrast, the Reynolds number alone does not adequately reflect this variability, which depends more strongly on the local vortex density.

These results confirm the feasibility of ultrasonic techniques in turbulent flows, provided that the influence of local flow structures is taken into account—particularly for vibration monitoring of mixing grids in PWR cores.

***Keywords* — acoustic, non-destructive testing, assembly, vibration, turbulent flow, pressurized water reactors.**

I. Introduction

This work presents a study of ultrasonic wave propagation through a turbulent flow representative of the flow near a mixing grid in a Pressurized Water Reactor (PWR) fuel assembly.

Acoustic measurement is a non-destructive testing technique that enables accurate determination of a distance or displacement, provided that the acoustic velocity of the media traversed is known [1]. Conversely, it can also be used to determine the acoustic velocity if the distance is known. This method is particularly well suited to harsh environments, as it does not require visual access, unlike techniques such as laser interferometry.

It is therefore relevant to investigate how an ultrasonic wave propagates through a known fluid medium—such as water—when the fluid is in motion, and in particular to assess whether the flow alters the local acoustic velocity [2].

In laminar flow conditions, studies have shown that the acoustic wave is simply advected by the flow in the direction of propagation. This principle is exploited in ultrasonic flowmeter technologies [3]. However, in the case of turbulent flow, the wave propagation is disrupted by local velocity fluctuations within the fluid. These fluctuations locally modify the apparent acoustic velocity [4].

The real acoustic velocity in water can then be expressed as:

$$v_{real} = v_{theoretical} + \delta v \quad (1)$$

δv denotes the perturbation induced by turbulence.

Quantifying this deviation δv is essential in order to apply a correction to the measurement or simply consider it as an uncertainty. If this correction is neglected and the acoustic velocity is assumed to remain constant and equal to its theoretical value, an error will be introduced in the estimation of the distance or displacement.

To gain a better understanding of the influence of turbulent flow on ultrasonic wave propagation, it is relevant to first investigate the isolated impact of a single vortex. This can be achieved by generating Von Karman instabilities [5] and analyzing the behavior of an ultrasonic wave propagating through these vortical structures. The acoustic setup is positioned perpendicular to the direction of the fluid flow. It is important to note that a vortex exhibits non-zero transverse velocity components relative to the main flow direction. Experimental results reveal a sinusoidal fluctuation in the time of flight of the ultrasonic wave as it passes through the vortex. This variation is directly attributed to the transverse velocities induced by the vortex field, which locally accelerate or decelerate the propagation of the ultrasonic wave.

It is then essential to quantify the measurement fluctuations induced by a turbulent flow, which is characterized by the presence of multiple vortices of varying scales.

In this paper, the motivation and relevance of this analysis will be firstly presented. Then, the experimental setup implemented to conduct the study will be described in detail.

Finally, results obtained on ultrasonic wave propagation within turbulent flow will be analyzed and discussed.

II. Interest of the study

Pressurized Water Reactors (PWRs) represent the dominant technology in the French nuclear fleet. The core of a PWR consists of fuel assemblies composed of metallic grids that hold 17 by 17 fuel rods. Each rod is a metallic tube filled with uranium pellets where nuclear fission occurs. The rods are not rigidly fixed to the grids but are held in place by springs and dimples at the mixing grids. This configuration allows for thermal expansion but also introduces mechanical contact points that can lead to vibration phenomena.

Under such conditions, vibrations may occur between the mixing grid and the fuel rods. Two main types of vibration have been identified:

- Fretting, a form of mechanical wear resulting from vibrations induced by the high-velocity coolant flow (serving as both moderator and heat transfer fluid), with axial flow rates around 500 m³/h and transverse components reaching up to 75 m³/h. This generates vibrations typically around 70 Hz with amplitudes of approximately 10 µm [6].
- Seismic-induced vibrations, which may also excite the fuel assemblies, but with significantly lower frequencies (< 10 Hz) and larger amplitudes (> 500 µm) [7].

These vibration phenomena can lead to mechanical degradation of the fuel rods, potentially resulting in cladding failure and the release of radioactive material into the primary circuit, thus compromising reactor safety and performance.

The present study aims to evaluate the feasibility of measuring such vibrations, particularly those induced by seismic activity, under realistic conditions. It is therefore assumed that the grid displacements can reach up to 500 µm, and the goal is to assess whether these vibrations can still be detected accurately in the presence of turbulent flow.

To better understand and ultimately model these phenomena, experimental facilities such as HERMES P, located on the POSEIDON platform at CEA Cadarache, have been developed. These experimental loops replicate full-scale (1:1) thermal-hydraulic conditions of a PWR core, excluding the irradiation aspect, with water temperatures approaching 320 °C, pressures around 155 bar, and flow rates on the order of 500 m³/h.

To measure the vibrations without altering the geometry of the test section, non-destructive testing (NDT) techniques must be employed. Ultrasonic measurement is a promising approach, as it allows for displacement tracking without physical contact or external disturbance. However, to ensure the reliability of such measurements in PWR-like conditions, it is essential to thoroughly understand the behavior of ultrasound propagation in turbulent flow regimes [8], which forms the central focus of this study.

III. Experimental setup

The following section provides a description of the test section as well as the implemented acoustic setup, as detailed in Figure 1.

A. Test section

The test section consists of a closed-loop water circuit with a square flow channel measuring 5 cm × 5 cm in cross-section and 1.20 m in height, made of PMMA [9]. The flow is driven by a pump with a capacity ranging from 0 to 75 m³/h. Although this flow rate is significantly lower than that observed in a Pressurized Water Reactor (PWR) or in the HERMES P test loop, the flow regime remains dynamically comparable due to a maximum Reynolds number of 4.2×10^5, compared to approximately 5×10^5 for a PWR.

An obstacle is placed at the center of the test section to generate vortex shedding phenomena similar to those occurring around a fuel assembly. This configuration makes it possible to distinguish two study regions: an upstream zone characterized by flow without vortex shedding, and a downstream zone with a high density of vortical structures. Such a geometry allows the analysis of the effects of turbulence and vortex density on ultrasonic wave propagation under conditions representative of a PWR environment.

B. Ultrasonic device

The experimental setup employs two 10 MHz ultrasonic transducers positioned face-to-face on either side of the channel, enabling through-transmission measurements. The transducers are mounted using lateral flanges attached to the channel walls; these flanges can be moved along the vertical axis, allowing acoustic measurements to be taken either upstream or downstream of the central obstacle.

It is important to note that the ultrasonic waves propagate perpendicularly to the main flow direction. As a result, the waves are not advected by the flow itself, but their propagation path can be locally disturbed by the presence of vortical structures within the turbulent flow.

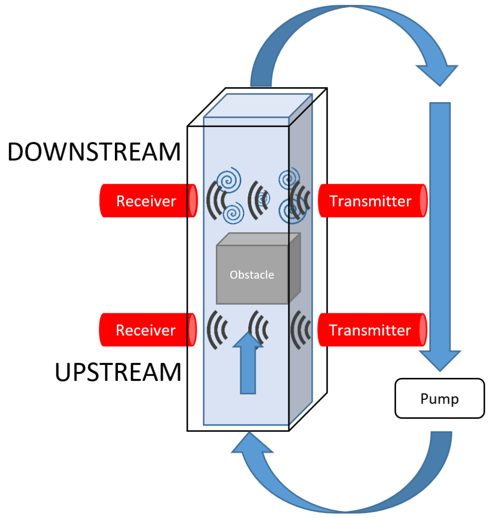

Figure 1: Diagram showing the test section with the position of the acoustic device upstream or downstream of the obstacle.

IV. Signal acquisition and processing

The ultrasonic path between the two sensors passes successively through three media: the first PMMA wall of the channel, then the flowing water, and finally a second PMMA wall before reaching the receiving sensor. This configuration involves three distinct layers—PMMA, water, and PMMA—for which the respective acoustic velocities must be known in order to accurately interpret the measured time of flight. Since the thicknesses of these media remain constant throughout the experiments, and the acoustic velocity in PMMA does not vary over time, only the acoustic velocity in water may fluctuate. The measured time of flight corresponds to the first detected signal, that is, the fastest path between the emitter and the receiver, meaning a path without any reflections within the media, and is given by the following expression:

$$TOF = \frac{d_{PMMA1}}{v_{PMMA1}} + \frac{d_{water}}{v_{real}} + \frac{d_{PMMA2}}{v_{PMMA2}} \quad (2)$$

with *TOF* representing the time of flight, *d* the distances, and v_{PMMA} the theoretical acoustic velocity of PMMA. The term v_{real} defined in Equation (1), represents the theoretical acoustic velocity of sound in water, with an additional perturbation due to turbulence δv. In Equation (2), all terms are constant except for v_{real}. By correcting Equation (2) to remove the constant PMMA terms, the following Equation (3) can be obtained:

$$TOF = \frac{d_{water}}{v_{real}} + K \quad (3)$$

where K is a constant term.

Thus, a fluctuation in the corrected time of flight originates only from a variation in the real acoustic velocity in water, since the terms are not independent and the water distance remains constant. The goal is then to quantify these fluctuations.

Given that it is difficult to accurately measure the real acoustic velocity in water in real time to correct for fluctuations, we assume that the real velocity is constant and equal to the theoretical velocity. Under this assumption, and according to Equation (3), the time-of-flight fluctuations can be interpreted as measurement fluctuations on the water distance.

The error in the distance measurement is calculated using Equation (4), under the assumption that the acoustic velocity of sound in water remains constant.

$$\Delta_{distance} = \Delta_{TOF} \times v_{water\ theoretical} \quad (4)$$

To evaluate the fluctuations in the time of flight, ten acquisitions of the first signal (as described by Equation 2) are performed for each configuration, while keeping the sensor positions and the flow rate/Reynolds number constant. These sets of measurements are repeated at different flow rates, both upstream and downstream of the obstacle.

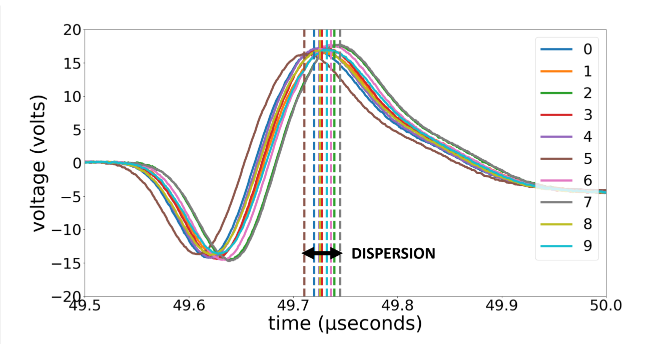

Figure 2: Example of time-of-flight dispersion measured with peak detection (maximum) for a batch of 10 measurements with the same flow rate and sensor position

For each set, the time of flight is determined by identifying the peak of the received signal, as shown in Figure 2. The mean value is calculated and fluctuation (dispersion) is then quantified by calculating the standard deviation at 1 σ of the time-of-flight values. The standard deviation serves as a relevant indicator of measurement variability around the mean value. It follows that a larger standard deviation reflects greater fluctuations in the acoustic velocity of the water, induced by turbulence.

By referring back to Equation (4), it is logical to substitute the uncertainties with the standard deviation measured at 1σ, leading to Equation (5).

$$\sigma_{distance} = \sigma_{TOF} \times v_{water\ theoretical} \quad (5)$$

In this way, TOF uncertainties caused by turbulence-induced speed perturbations are measured by the standard deviation, and can be translated as an error or uncertainty in the distance measurement.

V. Results and discussion

The results represent the standard deviation in distance as a function of the Reynolds number (flow rate) in Figure 3, for sensor positions located upstream or downstream of the obstacle.

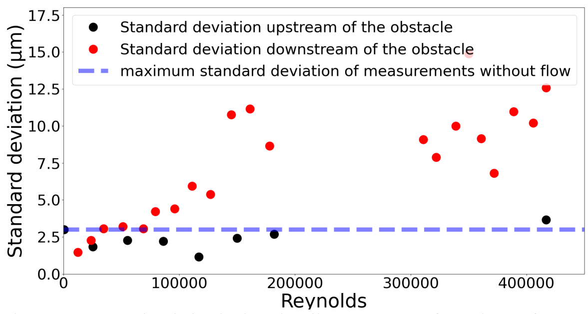

Figure 3: Standard deviation in distance as a function of Reynolds number for sensors placed upstream and downstream of the obstacle.

It is observed that when the sensor is positioned downstream of the obstacle—i.e., in the region with a high density of vortical structures—the standard deviation increases with the flow rate, following an approximately linear trend up to a Reynolds number of $1.5{\times}10^5$. However, it is important to highlight that the standard deviation never exceeds 15 µm for a distance of 5 cm of water, even under the most turbulent conditions.

Conversely, when the sensor is located upstream of the obstacle—where the flow exhibits low vorticity—the standard deviation remains nearly constant regardless of the Reynolds number. Even at a Reynolds number equal to $4.2{\times}10^5$, the standard deviation remains below 4 µm, for a distance of 5 cm of water.

It should also be noted that a nonzero standard deviation is recorded even in the absence of flow. This is attributed to the inherent limitations of the measurement system. Nonetheless, repeatability and reproducibility tests have demonstrated that, without flow, the standard deviation consistently remains below 3 µm, which is considered the baseline measurement uncertainty for this experimental setup.

It is important to emphasize that the Reynolds number is not a reliable indicator for assessing the dispersion of acoustic measurements caused by turbulence. Instead, the variability is more strongly correlated with the local density of vortical structures. Therefore, the observed fluctuations in time-of-flight measurements can be more accurately attributed to the presence of vortices in the measurement region.

VI. Conclusion

This study has assessed the impact of turbulent flow on ultrasonic wave propagation within a channel representative of conditions in a Pressurized Water Reactor (PWR). The results demonstrate that turbulence, particularly the local density of vortical structures, induces measurable fluctuations in the time of flight of ultrasonic waves. These fluctuations, quantified via the standard deviation, reflect a dispersion in the measurements that can reach up to 15 µm in regions with higher vortex density. This means that the mean value is determined with an uncertainty of ±15 µm but also that the accuracy of the measurement cannot be less than 15 µm for a distance of 5 cm of water. It is also shown that the Reynolds number alone is not a reliable indicator of this dispersion. The primary factor influencing measurement variability is the local density of vortices.

These knowledge of the accuracy of distance measurements is of great importance for the development of acoustic monitoring methods under realistic PWR conditions, especially for the detection of mechanical vibrations such as those induced by seismic excitations. The results confirm the feasibility of acoustic measurements for displacements on the order of 500 µm (seismic events), as measurements can be made with an accuracy of 15 µm even in the presence of significant turbulence, if the water distance is equal to 5 cm.

However, displacement measurements, such as mechanical vibration detection, are typically performed using reflected ultrasonic signals. It would therefore be of interest to investigate the impact of vortical structures on measurements performed in reflection, rather than in transmission as done in the present study.

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