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STUDY OF ULTRASONIC PROPAGATION THROUGH VORTICES FOR ACOUSTIC MONITORING OF HIGH-TEMPERATURE AND TURBULENT FLUID

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Abstract. Ultrasonic monitoring in high temperature fluids with turbulences requires the knowledge of wave propagation in such media and the development of simulation tools. Applications could be the monitoring of sodium-cooled fast reactors. The objectives are mainly acoustic telemetry and thermometry, which involve the propagation of ultrasounds in turbulent and heated sodium flows.

We developed a ray-tracing model to simulate the wave propagation and to determine wave deviations and delays due to an inhomogeneous medium. In previous work we demonstrated the sensitivity of ultrasounds to temperature gradients in liquid sodium. To complete that study, we need to investigate the sensitivity of ultrasounds to vortices created in a moving fluid. We designed a specific experimental setup called IKHAR (Instabilities of Kelvin-Helmholtz for Acoustic Research) in order to assess the validity of the ray-tracing model and the potential of ultrasounds for monitoring such fluid.

In this experiment, Von Karman instabilities were created in a flow of water. Fluid temperature was homogeneous in our experimental setup. Through a careful choice of the parameters, periodic vortices were generated. The experiment was also simulated using Comsol[®] to allow discussion about repeatability. The through-transmission method was used to measure wave delays due to the vortices. Arrays of transducers were used to measure time of flight variations of several nanoseconds with a high spatial resolution.

Results were similar to simulation results. They demonstrate that beam delays due to vortices can be measured and confirm the potential of ultrasounds in monitoring very inhomogeneous fluid media such as liquid sodium used as coolant fluid in nuclear fast reactors.



Introduction

The Sodium-Cooled Fast Reactor (SFR) has been chosen by France as the reference option in the framework of the Generation IV International Forum [1]. For this kind of reactor, it is necessary to develop a specific instrumentation, compatible with liquid sodium used as coolant, and to meet the Generation IV requirements, particularly in terms of reliability.

In the area of the reactor between the outlet of the fuel assemblies and the upper core structure, there is a need for some thermometry and telemetry instrumentation. Thermometry would be used to monitor the assembly sodium outlet temperature and telemetry would be used to detect the movements of these assemblies. Ultrasounds are suitable for these measurements because they propagate rapidly in liquid sodium, and are weakly attenuated. Furthermore, with this method, the transducer can be placed far from the measurement area in order to minimize its effect on the sodium flow (as pressure loss).

However, in this area, the sodium flow is turbulent and presents significant temperature variations. Depending on the orientation of the acoustic beam, these inhomogeneities may result in deviations and changes in the ultrasonic time of flight, which could interfere with measurements.

Numerical codes, such as AcRaLiS (Acoustic Ray in Liquid Sodium) [2] or CIVA [3], have been developed to compute ultrasonic propagation in such environments. Some experiments in static thermal inhomogeneous medium have already been performed to verify a part of the model used in AcRaLiS simulation code [4]. However, in a turbulent medium, the chaotic nature of the flow makes the experimental verification of the model complex. To deal with this issue, an experimental bench named IKHAR (Instabilities of Kelvin-Helmholtz for Acoustic Research) has been set up. It produces a flow of water with specific and reproducible vortices which are crossed by ultrasonic beams.

After a short presentation of the numerical model used in AcRaLiS, we will describe the functioning of the IKHAR experiment bench and the way the acoustic measurements were realized. Then we will discuss the IKHAR experimental results and their comparison with numerical results obtained with Comsol[®] and AcRaLiS. We will describe the way Comsol is used to realize simulations of the fluid dynamics in IKHAR, and how the numerical thermo-hydraulic data obtained are used with AcRaLiS.

1. The acoustic ray model of AcRaLiS

The simulation of an acoustic wave propagation in a fluid medium may be realized with numerical models based on different kinds of theory or method, such as:

- the ray theory, which consists in discretizing the wave front of an ultrasonic wave, and following the path independently of each point on this front. The path followed by these points will appear as a ray whose behavior may be quite close to that of a light beam [5].
- the finite elements method consists in discretizing the medium in small volumes or surfaces, where partial differential equations are solved. Application of this method requires the solution of equations in the entire medium.
- the spectral finite elements method is a method similar to the finite elements method, but in the frequency domain. Moreover, its particular implementation allows it to be more accurate and faster than a conventional finite elements method when the wavelength of the wave to propagate is very small in comparison with the propagation medium [6].

The finite elements and spectral finite elements method can accurately simulate wave propagation in a complex fluid medium (inhomogeneous temperature and turbulent flow) if the system of partial differential equations is well adapted to the medium. This accuracy, however, is related to the size of the mesh: the smaller the wavelength is, the smaller the size of the elements has to be. As here the frequency of the propagating wave is of the order of a few megahertz (wavelength approximately equal to 2.3 mm in 500°C liquid sodium) and as the propagation length is over several tens of centimeters, then the number of elements in which the partial differential equation will be resolved is very important. That implies significant costs calculations.

The ray method is much faster for high frequency applications because it only takes into account the parts of the medium in which the ultrasonic waves propagate. Moreover, this method is able to conveniently consider both the effects of temperature and turbulence in the medium. It is for these reasons that we have chosen to implement a code based on this method. This code is called AcRaLiS, for Acoustic Ray Theory in Liquid Sodium.

Following previous work, we coded AcRaLiS as an iterative code [7]:

- At time t , a point of the wavefront is situated at the coordinates of the point \vec{x}_p . At this point the wavefront has a propagation direction \vec{N} , and celerity c .
- Taking into account these characteristics of the wavefront, and the local flow velocity \vec{v} and the temperature of the medium, the position of this point on the wavefront at the next time step is computed.
- The calculation is repeated by taking into account the new features of the wavefront and the thermo-hydraulic parameters of the medium at the new point.

The equations used for this calculation are the following:

$$\frac{d\vec{x}_p}{dt} = \vec{v}(\vec{x}_p, t) + \vec{N}(\vec{x}_p, t) c(\vec{x}_p, t) = \vec{v}(\vec{x}_p, t) + c(\vec{x}_p, t) \frac{c(\vec{x}_p, t)}{\Omega} \vec{s}$$

$$\frac{d\vec{s}(\vec{x}_p)}{dt} = -\frac{\Omega}{c} \vec{v}c - \vec{s} \wedge (\vec{v} \wedge \vec{v}) - (\vec{s} \cdot \vec{v}) \vec{v}$$

where \vec{x}_p is a point on the wavefront, \vec{v} the flow speed, \vec{N} the ray propagation direction, and \vec{s} the slowness vector, as $\vec{s} = \frac{\vec{N}}{c + \vec{v} \cdot \vec{N}}$, and $\Omega = 1 - \vec{v} \cdot \vec{s}$.

At the end of the calculations, it is easy to determine the shape of the wavefront at each time step.

The calculation of the energy is performed using the method of summation of Gaussian beams [8]. As the remainder of this document concerns the accuracy of the wavefront shape calculated by the code and not the amplitude of the signal, the Gaussian beams summation method will not be described here.

The part of this model that calculates interactions between ultrasounds and the medium temperature was already validated using an inhomogeneous temperature field in silicon oil [4]. In the work presented here, we designed a specific experiment to estimate the AcRaLiS accuracy to calculate the interactions between ultrasounds and a turbulent flow. To this end, an experimental bench named IKHAR was set up.

2. The IKHAR experimental bench

The difficulty of producing a turbulent flow of water in which to propagate ultrasonic waves, is to control this flow, to repeat it if necessary, and especially to determine the flow velocity field. This last point is important because without the knowledge of the velocity field it is not possible to use AcRaLiS (or other code) to simulate the propagation of ultrasound and so to compare the numerical simulation results with the experimental ones.

2.1. Vortices generation

We present here the flow turbulences produced by generating Von Karman vortices. In previous work we produced Kelvin-Helmholtz instabilities [2], and we want now to test our model with Von Karman instabilities which are simpler to simulate with Comsol[®] (cf. next chapter).

Von Karman instabilities are vortices that occur downstream of a cylindrical obstacle placed in a steady-state water flow [8]. In our experiments, the water flow speed is about one meter per second.

These vortices have the advantage of being periodic. This period depends directly on the velocity of the flow upstream of the obstacle and the geometry of this obstacle. This relationship is expressed by the Strouhal number which is defined as follows [8]:

$$St = \frac{f \cdot D}{V}$$

where f is the frequency of vortex detachment, D is the diameter of the obstacle, and V is the velocity of the flow. St is the Strouhal number, and has a constant value of 0.2 for a cylindrical obstacle as in our experiment.

Thus, once the speed of the water flow is adjusted, all the generated vortices have similar thermohydraulic characteristics. In addition, the geometry of the flow velocity field is simple and can be obtained through Computational Fluid Dynamics (CFD) simulations.

It is the experimental bench named IKHAR which generates these vortices. IKHAR is a hydraulic loop generating a water flow at a speed of $3 \text{ m}\cdot\text{s}^{-1}$ in a pipe of rectangular section (11cm x 4 cm) [2]. This section is 3.1 m long. The mean flow velocity is measured by means of an electromagnetic flowmeter. The water flow reaches a steady-state in the first half of the section, and then meets the cylindrical obstacle. Von Karman vortices are generated in the second part of the section which is instrumented with ultrasonic transducers. A diagram of the test section of the IKHAR bench is shown in the figure below.

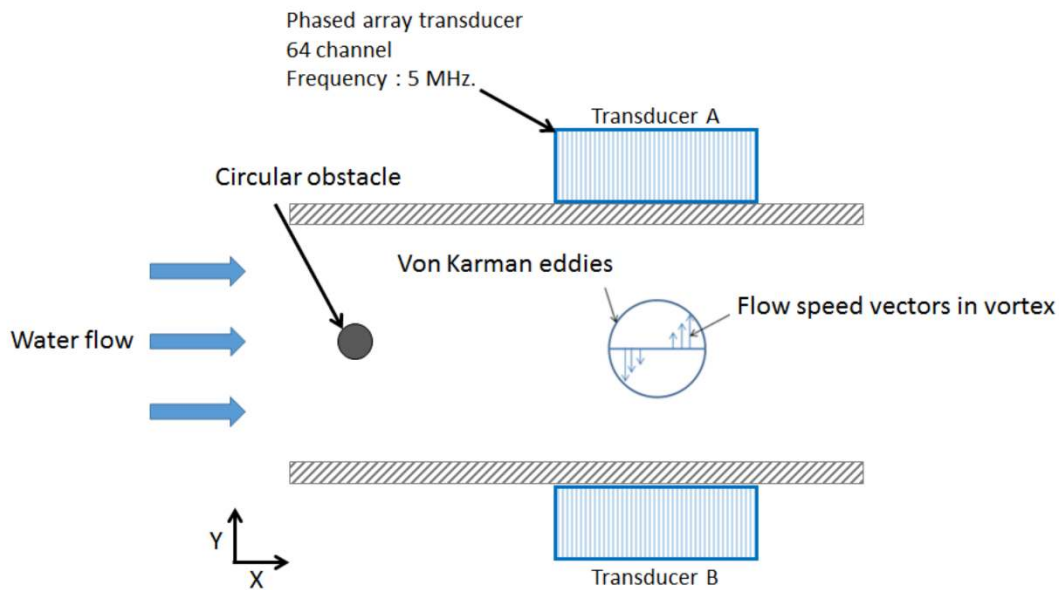


Figure 1. Diagram of IKHAR test section.

The objective of this experiment being to measure the influence of a disturbed velocity field on the propagation of ultrasounds, two ultrasonic transducers are arranged face to face on each side of the produced vortices to accurately measure the wave distortion.

2.2. Acoustical measurement and signal processing

The transducers used to measure the influence of vortices on the propagation of ultrasound are two identical one dimension linear arrays. They each have 64 elements (each element being 0.5 mm wide and 10 mm high) with an inter-element space of 0.1 mm. Their central frequency is 5 MHz.

These two transducers are arranged face to face on each side of the test section and both work as emitter and receiver. They simultaneously emit an acoustic wave, then each transducer receives the propagating signal from the other transducer.

When the wave reaches the transducer, the times of flight are recorded independently on each element of the phased array. The small size of the elements allows us to accurately determine which parts of the wave front have been delayed and which parts have been accelerated.

The Mach number, which is the ratio between flow velocity and acoustic wave velocity, is here very small, of the order of 0.06%, and the time of flight variations are only of a few nanoseconds. To measure these fine variations several operations must be performed on the acquired signal.

First we measure the time of flight of the acoustic signal received by each element. This measure is realized using an interpolation to enhance the time resolution. Then we eliminate some intrinsic time of flight variations that are independent of the vortex passage and constant during acquisition. These variations may result from the disposition of the two transducers (whose surfaces may not be perfectly parallel), the shape of the transmitted signal (the wave front may be slightly curved) or the intrinsic characteristics of the transducers.

These constant variations are independent of the flow and are a continuous component of all the acquired signal. On the contrary, the time of flight variations due to the vortices in the flow are time-dependent and are alternately positive and negative, depending on the part of the vortex on which the measurement is made.

Also, by averaging the time of flight measured by each element on a large number of acquisitions (several thousand), variations due to flow instabilities tend to disappear, while the continuous component is enhanced.

Then, by subtracting this average to the time of flight measurements, we get the variations which are only due to the passage of vortices. These variations appear on the following figure.

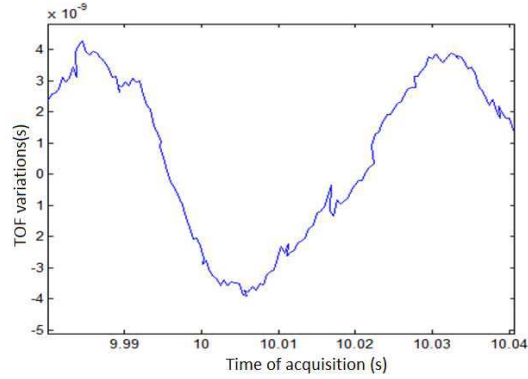


Figure 2. Influence of Von Karman vortex on time of flight variations.

2.3. Experimental results

These measurements, realized simultaneously on the two transducers during several seconds and reported as a function of the acquisition duration, gave the following results:

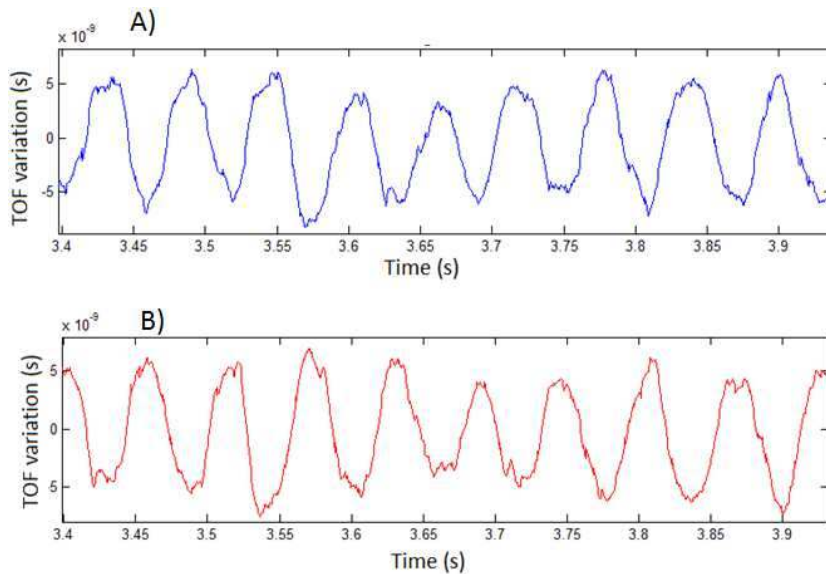


Figure 3. Time of flight measurement on the two transducers (A and B) at the same time.

The simultaneous use of two transducers as emitter and receiver placed face to face ensures that these variations are due to the flow velocity field.

Indeed, if an acoustic wave propagating in one direction is accelerated by the flow, the acoustic wave propagating in the opposite direction at the same time will be slowed. Thus, the influence of the flow on the celerity of the waves is vectorial, unlike the effect of temperature which is scalar.

Figure 4 presenting the variations in time of flight of two waves propagating in opposite directions shows clearly these opposite variations. This confirms that these small changes are

not due to possible temperature changes or evolution in the distance between the two transducers.

These time of flight variations are periodic, with a frequency around 17 Hz (as predicted with a Strouhal number equal to 0.2) and a regular amplitude in the order of 11 ns. These results confirm the periodic and stable generation of Von Karman vortices in the IKHAR bench.

3. Comparison with numerical data

For the comparison of experimental data with numerical results, the difficulty lies in obtaining a numerical mapping of the flow velocity field in vortices. This mapping of the flow is subsequently used for simulating the propagation of ultrasound with AcRaLiS. In this study we obtained this mapping of the water flow within the IKHAR testing section by running a Computational Fluid Simulation in Comsol[®]. This solution is simple and provides a realistic mapping of the flow. To get a more accurate mapping, the solution could be to measure the velocity of flow in IKHAR with an optical technique like Particle Image Velocimetry. However, this solution is more complex to implement and was not used in these first comparisons.

3.1. Thermo-hydraulics simulations

These simulations were performed using Comsol Multiphysics software. They are two dimensional and use the physical module named "Laminar Flow". This module solves the Navier-Stokes equations without averaging the turbulences, like the models based on RANS (Reynolds Average Navier-Stokes) methods. The geometry of the simulation is presented in Figure 4 and Figure 5.

The water flow enters the section with a direction parallel to the positive axis X. To be more realistic, a velocity profile is given to the flow of water as it enters the simulated section, that is, on each side of the obstacle. This profile is shown in Figure 4. The average value of the velocity profile used is the average value measured by the electromagnetic flowmeter in the IKHAR loop.

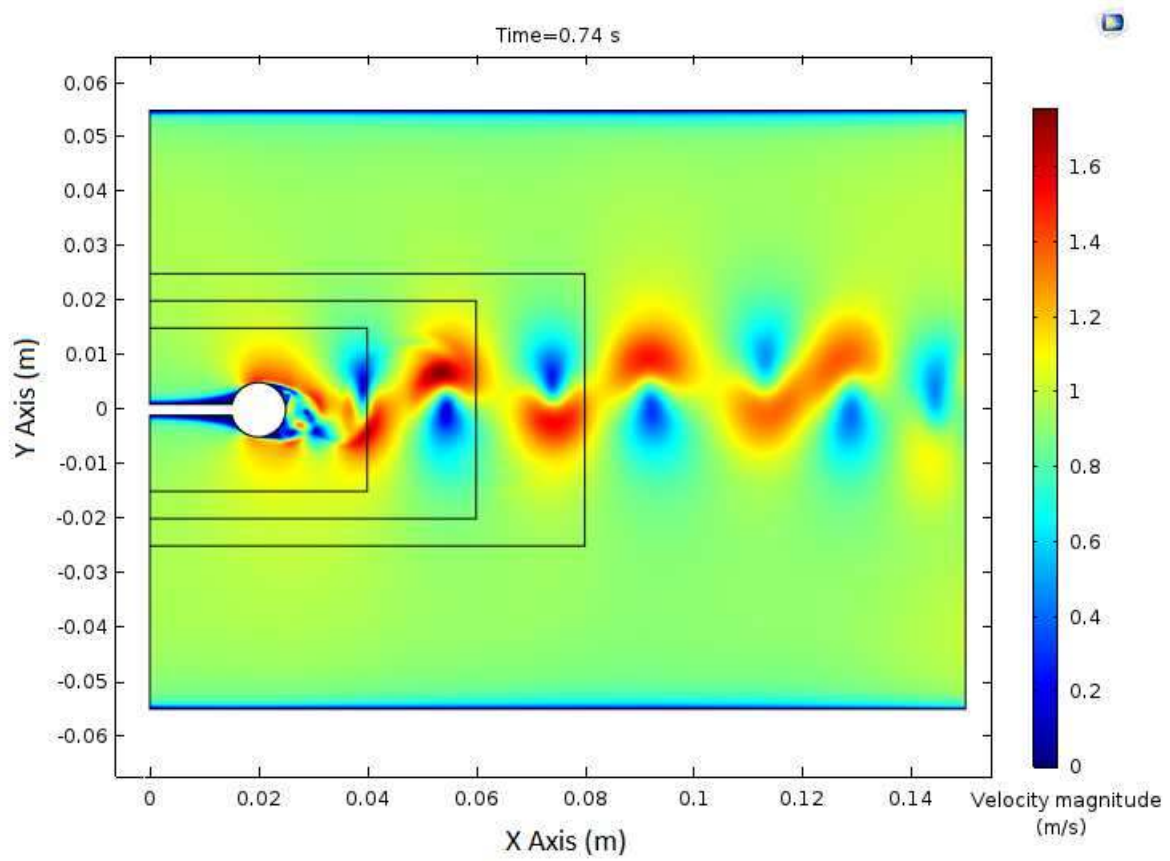


Figure 4. Mapping of velocity field amplitude in XY plan. CFD simulation of IKHAR test section.

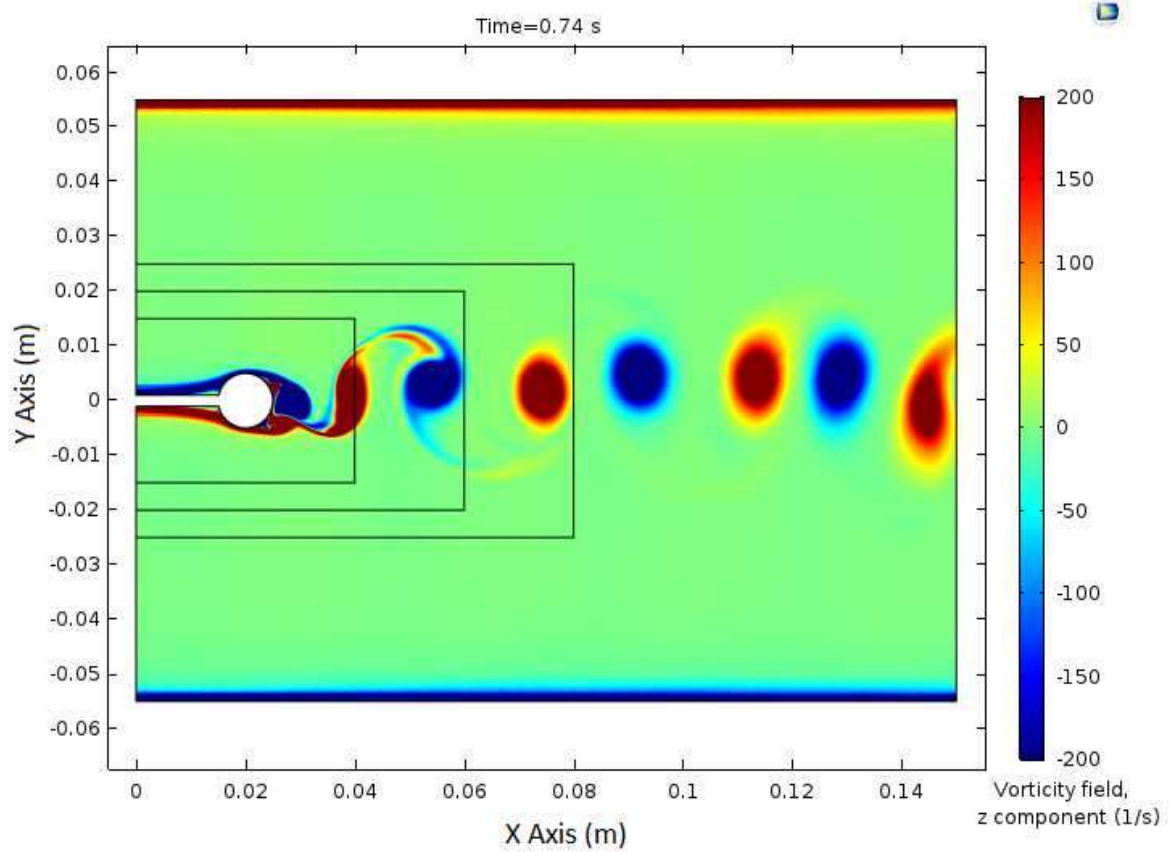


Figure 5. Mapping of vorticity field along Z axis. CFD simulation of IKHAR test section

These figures show the vortices generated by the cylindrical obstacle, the so-called Von Karman vortices. For a better visualization of the eddies, the flow vorticity is also displayed (cf. Figure 5). Vorticity is calculated by applying the curl operator to the flow velocity field.

3.2. AcRaLiS simulations

The acoustic rays were emitted from a horizontal line at $Y=-0.055$ m and between $X=0.075$ m and $X=0.113$ m (see Figure 6). This 3.8 cm long emitter line was therefore representative of the transducer used. 213 rays were emitted orthogonally to the line. The time of flight of each acoustic ray was recorded on a receiving line of identical size, located at $Y = 0.055$ m. The following figure describes this arrangement.

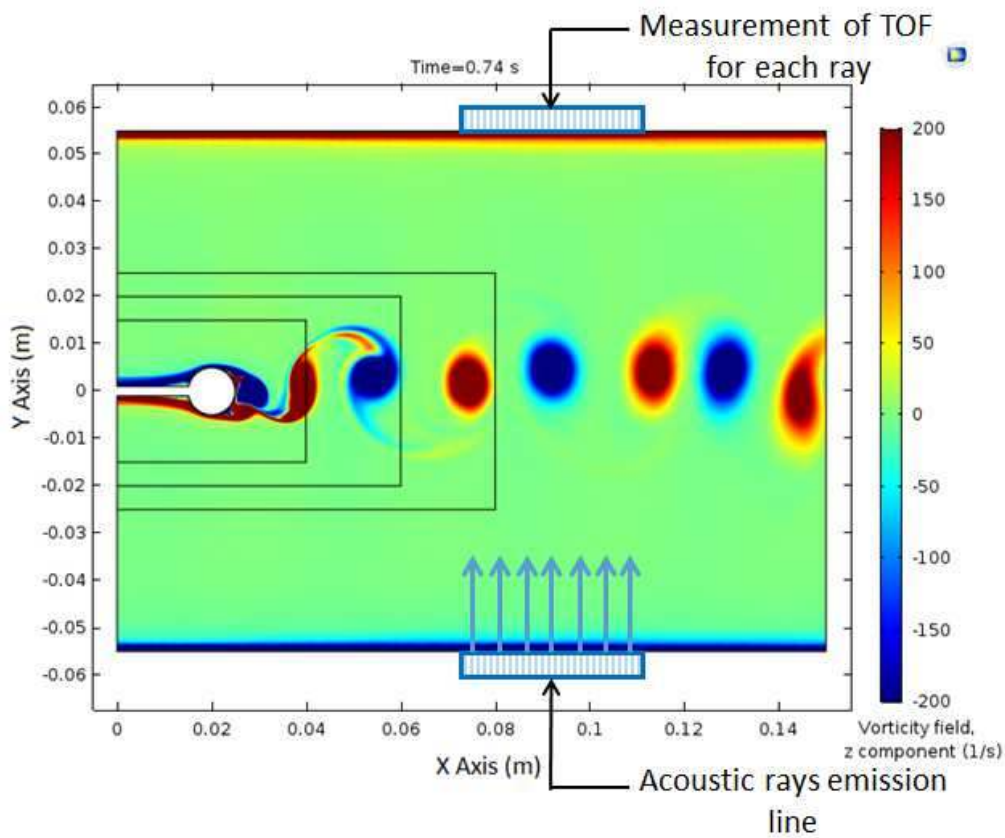


Figure 6. Position of acoustic rays emission line.

The result obtained - presented in Figure 8 - is consistent with the velocity field through which the waves are propagating: the generated vortices rotating in alternating directions create fluid streams oriented along the (positive or negative) Y axis. It is these currents that are responsible for the time of flight variations.

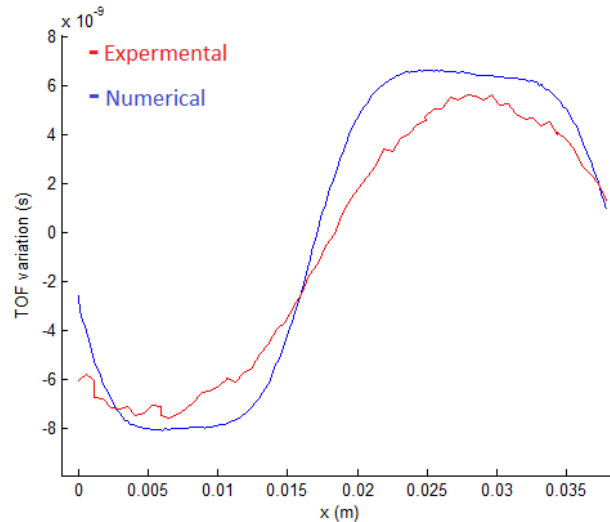


Figure 7. Comparison of numerical time of flight variations obtained with AcRaLiS and experimental data obtained with IKHAR.

Comparing the numerical results with experimental data collected on IKHAR gives very good results: variations appear in both cases as regular oscillations. These variation amplitudes are similar and the difference is only of 1.5 ns. Also, in this particular case the relative difference in oscillation frequency is of about 5 Hz.

Conclusion

These first comparison results are encouraging and suggest that a numerical tool based on the ray theory is efficient to calculate ultrasonic time of flight in a flowing medium whose velocity field is slightly disturbed.

It is likely that some of the differences observed when comparing the results come from the numerical mapping of the velocity field used for acoustic simulation. It is therefore possible to improve these results, either by improving the quality of the CFD simulation (by performing 3D computation) or by instrumenting the IKHAR bench test section to measure the actual velocity field (through an optical method like Particle Image Velocimetry).

From an experimental point of view, combining the generation of Von Karman vortices and the use of phased array transducers was a good choice. This allowed us to measure rapid, weak and localized variations in ultrasonic time of flight.

The next step will be to measure the deviation of the ultrasounds when passing through the vortices. Again, the use of phased array transducers whose elements have a width of 0.5 mm seems well suited to measure local and small variations in acoustic energy.

The methodology presented in this study was created to validate ultrasonic measurements, which are a good candidate for monitoring variations in inhomogeneous liquid sodium. This methodology is now confirmed with numerical and experimental results on separate phenomena. The final validation will require the development of a more complex experimental bench which could create known variations in both temperature and local velocity fields.

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