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A Hydroacoustic Model for the Identification of Incipient Cavitation: A Preliminary Study †

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Abstract: Recent research has focused on the dynamic control and regulation of hydraulic devices like pumps and turbines to enhance the efficiency of water systems. These devices are adjusted to maintain nearly optimal hydraulic conditions and operating efficiency, although achieving both can be challenging due to factors like machine type and changes in distribution patterns. Incipient cavitation, which can cause mechanical damage and reduce efficiency, presents a specific challenge. It produces a distinct noise which this study aims to detect through a proposed methodology. Using the LES WALE model in OpenFOAM and Lighthill's acoustic analogy, this research simulates and analyzes the noise generated by the dynamic of a confined flow. This work aims to be the starting point for more complex models.

Keywords: hydroacoustic; Lighthill; LES

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1. Introduction

Interest in the acoustics and noise propagation in fluids has surged in recent decades due to their significant implications across the industrial, environmental, and civil engineering domains. A notable area of concern is underwater radiated noise, which has prompted numerous international research projects due to its harmful impact on marine life's communication, physiological functions, and overall health. Studies have shown that fluid dynamic noise can adversely affect human mental and physical health, with examples like marine engineering noise from ship propellers.

Noise measurement in air is also crucial for assessing machinery operation in industrial applications. Cavitation, for instance, results in intense noise due to vapor bubble oscillations and collapses, posing challenges in naval propellers, pumps, and turbines when operating outside optimal parameters [1]. Rus et al. [2] linked acoustic signals to cavitation presence in turbines, developing models to predict such conditions based on noise patterns.

Addressing noise propagation within fluids generally involves solving the Navier–Stokes equations for compressible flows. However, practical challenges arise at low Mach numbers (below 0.3) due to the different characteristic scales of fluid dynamics and acoustics. Consequently, Lighthill's acoustic analogy has been employed, where fluid flows are treated as distributed acoustic source fields (quadrupoles), allowing for the separate resolution of fluid dynamics and acoustics.

This approach decouples the fluid dynamic simulation from the acoustic one; the first will be carried out to obtain the acoustic source, while the acoustic simulation is performed to obtain the acoustic pressure propagation in the domain. For accurate noise analysis, turbulence fields are crucial, and typically, computational simulations, like Large Eddy Simulations (LESs), are the way to go for the proper solution of a fluid dynamic field and an accurate acoustic source for a large number of scenarios.

Recent studies using acoustic analogies and eddy-resolving simulations have underscored the significance of noise generated by wake turbulence and linked tonal noise to specific flow phenomena. For heterogeneous media, new methods such as those proposed by Petris et al. and Montillo et al. [3–5] have advanced noise propagation modeling through varied materials and overlapping generation and propagation domains.

This work aims to give the first glance of a more complex model; several hydroacoustic simulations will be performed on confined geometries with different turbulence models and grid configurations. The effect of the different scenarios will be compared in order to obtain a general understanding of the acoustic problem for the shown cases.

2. Materials and Methods

Hydroacoustic simulation over various geometries consists of two distinct but interrelated simulations: the first is a fluid dynamics simulation that resolves the motion field to identify the acoustic source of the problem, and the second is an acoustic simulation that models the noise propagation using the scalar wave equation, the solution of which represents the acoustic pressure. The fluid dynamics simulation is conducted using various turbulence models (SSTk-omega, k-epsilon, and LES) to compare different configurations effectively.

Based on the fluid dynamic fields obtained, the noise source, known as the Lighthill source, is constructed using the acoustic analogy [6,7]. Once the acoustic source is known, it is possible to achieve noise propagation by using the Lighthill equation:

$$\frac{1}{c^2}\frac{\partial^2 p_a}{\partial t^2} - \frac{\partial^2 p_a}{\partial {x_i}^2} = \frac{\partial^2 \rho u_i u_j}{\partial x_i \partial x_j} \tag{1}$$

Here, p_a is the acoustic pressure, t is the time dimension, c is the speed of sound, x_i is the i-th space coordinate, and u_i represents the i-th velocity component. As can be seen in Equation (1), the acoustic source depends only on the fluid dynamic fields in particular; in this expression of the Lighthill equation valid for low-Mach number flows, the acoustic source depends only on the velocity field. The simulations were performed using second-order numerical schemes in both space and time. The acoustic domain coincides with the fluid dynamic domain, and all the boundaries were chosen to be completely reflective.

3. Results

The hydroacoustic simulation of a plane channel flow characterized by $Re_\tau = 395$ was performed. Different grid sizes were investigated to find the one that gives the best results in terms of accuracy and computational costs. The most accurate results are provided by LESs, as already mentioned by Piomelli et al. [8] However, in order to properly resolve an LES, it is necessary to adopt grids and timesteps that make it difficult to use for simulations characterized by a different Reynolds number. Once the fluid dynamics are obtained, the acoustic source term is evaluated for the channel. Then, the hydroacoustic simulation is carried out within the domain.

In Figure 1, the results in terms of the SPL (sound pressure level) of the hydroacoustic simulation of the channel are shown; the x coordinate was made non-dimensional with half of the channel's height.

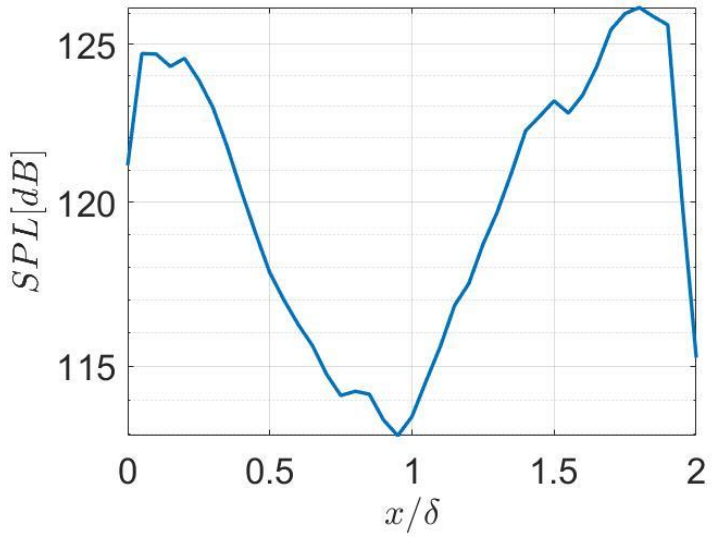


Figure 1. The SPL of the hydroacoustic simulation plotted on a line normal to the channel's walls.

4. Discussion

The findings presented in Section 3 highlight the significance of the chosen turbulence model. Specifically, it is crucial to achieve the most accurate solution possible in areas with strong velocity gradients, as these are responsible for the majority of noise generation. In this context, LES is undoubtedly the most reliable model. Moreover, in the case of flows characterized by a low Reynolds number, it is evident that accurately resolving turbulence at the wall is crucial for effectively studying noise generation. As a result, the application of wall functions is generally not recommended, as they can compromise the precision required for detailed noise analysis in such scenarios.

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