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Marine Propeller Noise Propagation within Bounded Domains

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Abstract

In the present work, we develop a new methodology to investigate the propagation of acoustic noise originating from a naval propeller, in a bounded marine environment. The propagation in a realistic environment is achieved by coupling the Ffowcs-Williams and Hawkings (FW-H) equation with the acoustic wave equation, overcoming some intrinsic limitations of the FW-H equation. First, the FW-H equation applied to the hydrodynamics field obtained from Large Eddy Simulation, accurately characterizes the propeller source in the acoustic near-field. Then, the propagation in the acoustic far-field is evaluated in an arbitrary domain by solving the acoustic wave equation. After validating the new proposed methodology, we investigate the propagation of the linear part of the noise generated by a naval propeller within a canal. The results show complex interaction between the noise source and the environment: the decay rate of the acoustic energy is strictly related to the distance of the source from the boundaries of the canal; local maxima and minima of the acoustic energy are observed resulting from the superposition of direct and reflected waves; the water-air interface introduces a peculiar asymmetry of the acoustic field associated with the interaction between the acoustic waves.

Keywords: Propeller, FW-H, FDTD, Noise propagation, Marine Environment

1 Introduction

The noise level in the ocean is mainly affected by commercial shipping (Hildebrand 2009) and causes danger to the marine fauna (Weilgart 2007; Erbe et al. 2019). More stringent regulations (Committee et al. 2012) on noise emission have led the shipbuilding companies to design silent class ships, to reduce their environmental impact. Numerical and physical experiments have revealed that in the low-frequency region ($< 200\text{ Hz}$), the primary source of noise produced by a ship is the propeller. However, predicting how the noise source interacts with the marine environment is still challenging due to the difficulties in performing numerical and physical experiments in real scenarios. Therefore, there is a need to develop numerical tools that accurately describe noise generated by complex systems and its propagation in the marine environment, as suggested by IMO (2014).

In laboratories for hydroacoustics experiments, increasingly sophisticated techniques have been developed, see for example (Felli et al. 2013) where a novel wavelet-based filtering procedure is adopted to investigate the near-field pressure fluctuations on a rudder at different deflection angles. The laboratory experiments are suitable to evaluate the acoustic signature of the propeller only in the vicinity of the noise source. Therefore, they are not suitable for obtaining realistic estimations for marine environments.

Experiments of the noise generated by ships in operational conditions have been performed, but typically these experiments are opportunistic, such as the measurements conducted in the Santa Barbara Channel (McKenna et al. 2012). Furthermore, the experimental conditions, such as the type of ship and the state of the environment, may be substantially different from case to case. Therefore, this type of measurements are suitable for acquiring broad estimations of the noise generated but are not suited to acquiring a better understanding of the interaction between the environment and the source.

Among the possible computational approaches, the acoustic analogy is widely in use in the scientific community. The acoustic analogy consists of a hybrid method where the computation of the acoustic field is decoupled from that of the hydrodynamic field. First, a hydrodynamic field is obtained using a computational method and, successively, the hydrodynamic data are given as input to the acoustic model. The hydrodynamic field is usually evaluated using unsteady Reynolds-averaged Navier-Stokes (RANS), Detached Eddy Simulations (DES), or Large-Eddy Simulation (LES) (see the review of Wang et al. (2006)). The acoustic reconstruction is obtained using the acoustic model of Lighthill (Lighthill 1952), Ffowcs-Williams and Hawkins (FW-H) (Ffowcs Williams and Hawkins 1969), and Curle (Curle 1955). Among the acoustic models, the FW-H equation is suitable for characterizing the noise generated by an immersed body in motion, and is of common use in the scientific community for the evaluation of propeller noise, see among others (Broglia et al. 2020; Bensow and Liefvendahl 2016; Keller et al. 2018). Specifically, for a ship propeller or, in general, a rotor, the noise associated to pressure and velocity over the blade surfaces peaks at Nn and n , where N and n are respectively

the number of blades and the revolution rate, whereas the noise associated with the wake is broadband and confined in the low-frequencies (see [Wang et al. \(2006\)](#) and [Cianferra et al. \(2019b\)](#) and literature therein reported). Among the available methods, LES and DES represent the best compromise between effectiveness and efficiency to resolve correctly the flow unsteadiness responsible of noise production ([Muscari et al. 2013](#); [Ianniello and De Bernardis 2015](#); [Posa et al. 2022](#)).

The main limitation of the acoustic analogy is the domain of applicability. For example, the propagation of the acoustic pressure given by FW-H is assumed to occur in an infinite homogenous domain, namely variation of the density field and associated speed of sound cannot be considered along with the presence of boundaries. The only remarkable exception is the presence of the free-surface, which can be simulated considering the half-space Green function within the solution of the integral terms composing the FW-H equation (see [Cianferra and Armenio \(2021\)](#) for a detailed discussion and application). Therefore, if the noise propagation in a realistic water basin is requested the literature acoustic analogy cannot be used. At this purpose, to overcome the FW-H limitations, a new methodology is herein proposed, which couple the acoustic analogy with a propagation model based on the numerical solution of the wave equation.

Among propagation models, two possible strategies are available: the first is to solve the Helmholtz equation, and the second is to solve the acoustic wave equation. The propagation of a simple acoustic source in a heterogeneous environment can be evaluated by considering the wave equation recast in the frequency domain, thus solving the Helmholtz equation, the first available strategy. In marine acoustics, several important applications of this method are found in the literature, such as [Sturm \(2005\)](#), where the authors studied the effect of complex morphology seabed on the propagation of a broadband pulse. Solving the Helmholtz equation has a low computational cost when the numerical domain is two-dimensional, but it has some limitations on the source's complexity (especially when complex directivity patterns are present). Therefore, over the years, problem-oriented methods have been proposed in literature since the suitability of a mathematical model may depend on the marine environment and the type of source. Three different aspects have to be considered: frequency of the source, depth of the water column, and the range-dependent environment, as discussed in the review paper of [Etter \(2012\)](#).

The second strategy is to solve the wave equation directly in the physical space-time domain, using discretization techniques to integrate the partial differential equations. This method is suitable for low-frequency sources in 3D domains of limited extension, up to a few kilometers, by far less than the distance covered when solving the Helmholtz equation in 2D slice. Consequently, the use of the wave equation in the physical domain was somewhat abandoned in the past due to the high computational cost and the interest in the propagation of the noise at very large distances, of the order of hundred kilometers. However, nowadays, interest has raised in the analysis of near-field acoustics

because of the anthropogenic noise (marine vessel, geophysical exploration,...) in in confined regions, such as canals, ports or fjords. In this case, the main advantage of the wave equation solution in the physical domain consists in the possibility of treating complex sources together with the environment's variability. However the use of this methodology in the marine environment is still unexplored, and few references are available, such as the work on marine hydrokinetic power devices by [Haffa et al. \(2018\)](#). Very recently, [Petris et al. \(2022\)](#) have investigated on the solution wave equation in the physical space using a Finite-Difference-Time-Domain (FDTD), validated the approach for simple archetypal sources (monopole, dipole, and quadrupole), considering the presence of boundaries, such as the free surface and the sea bottom.

On the other hand, extensive literature is available on room acoustics, which clearly deals with different conditions and applications, but shares some issues with underwater noise research. Taking advantage of methods developed initially for room acoustic, here we perform a nesting of the FW-H method within the FDTD algorithm discussed above, arriving at the development of this new methodology. This coupling allows the use of the two methods in their domains of applicability and to obtain the noise generated by, for example, a marine propeller and its propagation in a complex inhomogeneous environment.

The paper is organized as follows. In Section 2, we describe the novel methodology. In Section 3, we present a verification of the new coupled methodology. In Section 4, we study the problem of noise generated by a ship propeller and its propagation in the ambient fluid and discuss the results. In Section 5, we discuss the effects of the free surface on the propagation of noise generated by the propeller. Finally, Section 6 contains concluding remarks and suggestions for future work.

2 Methodology

The approach herein proposed aims to overcome the limitations of the FW-H equation by nesting its solution within the acoustic wave equation. The wave equation can evaluate the propagation in any-shaped bounded domains and inhomogeneous medium, considering the spatial variation of the density and of the speed of sound. The acoustic response of a complex marine environment is thus obtained by solving the differential wave equation in the physical space-time domain.

The methodology is illustrated in the flowchart in Fig. 1 and consists of three main steps: CFD Simulation, Acoustic Characterization of the source and Propagation Model.

In the first step, a computational hydrodynamic simulation is performed, which reproduces the fluid flow that generates the noise. We may notice that, at this stage, laboratory measurements could be used as well. The acoustic analogy allow to consider incompressible solvers for reproducing sources characterized by low Mach number. The accuracy of the numerical simulation must

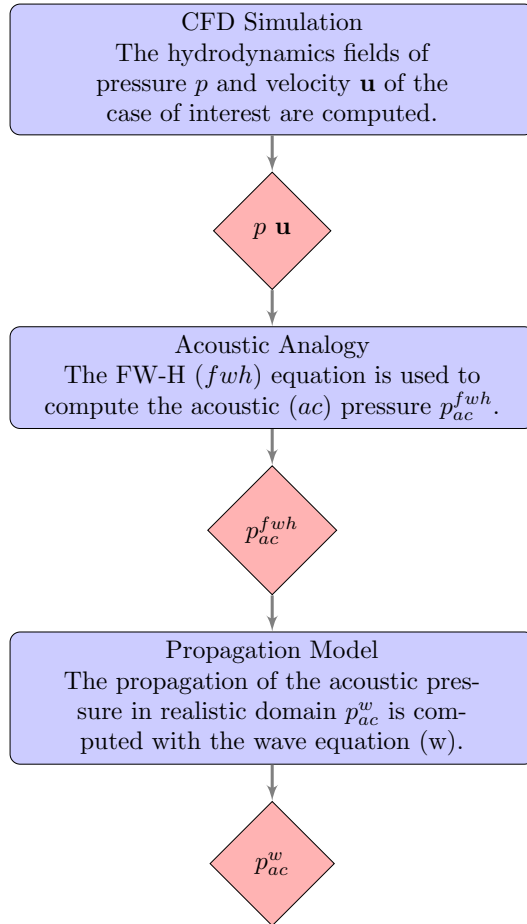


Fig. 1 Flowchart of the proposed methodology.

ensure that the fluid flow structures that can convert kinetic energy into acoustic energy (Lighthill 1952) are finely reproduced. The hydrodynamic pressure p and velocity $\mathbf{u}$ fields, which are the output of the CFD Simulation, are necessary to evaluate the acoustic pressure generated by fluid flow. In the present study, we use the hydrodynamic field obtained with an incompressible LES of an open-water propeller, discussed with details in Cianferra et al. (2019b); Cianferra and Armenio (2021) (Section 2.1).

In the second step, we use the integral form of the FW-H equation (Eq. 1), which enables the computation of the sound generated by an immersed moving body. The hydrodynamics field is used as input to compute the acoustic pressure p_{ac}^{fwh} at specific microphones arranged in a lattice surrounding the noise source. Therefore, the FW-H is used to characterize the noise generated by a complex source which exhibits a pronounced directivity pattern, in this case, a marine propeller in open-water (Section 2.2).

In the third step, the acoustic pressure signals collected at the FW-H microphones are given as input to the propagation model, where the environment's response is computed by solving the acoustic wave equation. Precisely, the acoustic signal p_{ac}^{fwh} collected in a lattice of microphones surrounding the noise source is used as a source (imposed boundary condition) within the FDTD algorithm (Section 2.3 and (Petrís et al. 2022) for in-depth details on the algorithm implementation). The differential wave equation is solved over a numerical grid representing the propagation domain of interest. Hereafter we describe the three steps and their coupling.

2.1 The Hydrodynamic Solution

The present acoustic study relies on the CFD simulation of the five-blade SVA-VP1304 (2011) benchmark propeller, described in the paper of Cianferra et al. (2019b) and also used in Cianferra and Armenio (2021).

The propeller is evaluated in open-water condition behind uniform flow in pull-condition; the advance ratio of the propeller and the Reynolds number of the numerical experiment are:

$$J = \frac{U_0}{nD} = 1.0683, \quad Re = \frac{U_0 D}{\nu} = 889680,$$

where $U_0 = -4 \text{ m/s}$ is the advance velocity, n is the rotational velocity in revolutions per seconds (rps) and $D = 0.25 \text{ m}$ is the diameter of the propeller. Defining the thrust S and the torque Q , the nominal values of the thrust (K_T) and the torque (K_Q) coefficients provided by the propeller with a advance ratio of $J = 1.0683$ are:

$$K_T = \frac{S}{\rho n^2 D^4} = 0.3538, \quad K_Q = \frac{Q}{\rho n^2 D^5} = 0.09096,$$

where $\rho = 1000 \text{ Kg/m}^3$ is the water density. The numerical domain of the CFD simulation is a cylindrical mesh, as depicted in Fig.2.

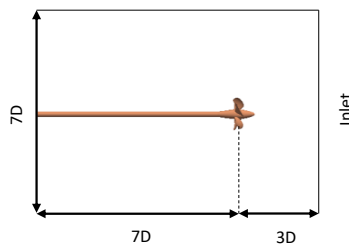


Fig. 2 Schematic of the numerical domain of the propeller CFD simulation.

The LES simulation was conducted in a rotating frame of reference, as proposed in the article of Kumar and Mahesh (2017). The incompressible

Navier–Stokes equations were rewritten as a function of the absolute velocity vector, taking into account the rotation effect and adding the Coriolis and centrifugal body force terms. The numerical experiment was performed within the OpenFOAM 2.3.0 framework, where the incompressible Navier–Stokes equations were solved using the Pressure-Implicit with Splitting of Operation (PISO) algorithm. The numerical schemes adopted were a second-order linear upwind scheme in space and a backward time integration, thus ensuring a second-order overall accuracy. The SGS stress tensor was modelled using the Dynamic Lagrangian model developed by Meneveau et al. (1996). A wall model was utilized, which allowed locating the first grid point off the wall at a distance of about $y^+ = 40$. The relative error of the integral quantities obtained with the numerical simulation were $e_{K_T} = 3.5\%$, and of $e_{K_Q} = 0.5\%$.

In Figure 3, coherent structures are visualized using the Q-Criterion (isosurface $Q = 20000$) coloured with normalized x -component of the vorticity vector. Both the tip vortex and the shaft vortex are visible, being the latter more intense and persisting downstream. Indeed, due to the pull-condition a strong vortex rolls-up on the shaft, which was also considered an important source of noise, at very low frequencies (see Cianferra et al. (2019b) for details).

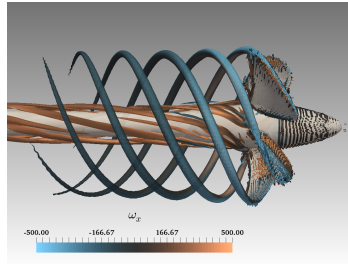


Fig. 3 Isosurface of the Q-Criterion ($Q = 20000$) coloured with normalized value of the x -component vorticity between the range $[-500, 500]$.

For the purpose of this study, the hydrodynamic fields of pressure p and velocity $\mathbf{u}$ were collected every 0.0018546 s , corresponding to 10 degree rotation angle.

2.2 Ffowcs-Williams and Hawkings Acoustics Model

The acoustic pressure field generated by the computed fluid flow and its interaction with the propeller is obtained by the numerical integration of the FW-H acoustic analogy. The acoustic pressure p_{ac}^{fwh} originated by a moving source within a fluid is evaluated with the following FW-H equation:

$$p_{ac}^{fwh}(\mathbf{x}, t) = \frac{\partial}{\partial t} \int_S \left[\frac{\rho u_i \hat{n}_i}{4\pi r |1 - M_r|} \right]_\tau dS + \frac{1}{c_0} \frac{\partial}{\partial t} \int_S \left[\frac{\tilde{p} \hat{n}_i \hat{r}_i}{4\pi r |1 - M_r|} \right]_\tau dS \quad (1)$$

$$\begin{aligned}
& + \int_S \left[\frac{\tilde{p} \hat{n}_i \hat{r}_i}{4\pi r^2 |1 - M_r|} \right]_\tau dS + \frac{1}{c_0^2} \frac{\partial^2}{\partial t^2} \int_W \left[\frac{T_{rr}}{4\pi r |1 - M_r|} \right]_\tau dW \\
& + \frac{1}{c_0} \frac{\partial}{\partial t} \int_W \left[\frac{3T_{rr} - T_{ii}}{4\pi r^2 |1 - M_r|} \right]_\tau dW + \int_W \left[\frac{3T_{rr} - T_{ii}}{4\pi r^3 |1 - M_r|} \right]_\tau dW
\end{aligned}$$

where $T_{ij} = \rho u_i u_j + (\tilde{p} - c_0^2 \tilde{\rho}) \delta_{ij}$ is the Lighthill tensor, $\tilde{p} = p - p_0$ denotes the fluid dynamic pressure perturbation with respect to the reference value p_0 , ρ is the bulk density, $\tilde{p} - c_0^2 \tilde{\rho}$ is deviation from an isentropic behaviour, $\hat{n}$ is the (outward) unit normal vector to the surface element dS , dW is the volume element, $r = |\mathbf{x} - \mathbf{y}|$ is the source-observer distance, being $\mathbf{x}$ the coordinate of the position of the microphone and $\mathbf{y}$ the coordinate of the source, $\hat{r}_i$ is the i -component of the unit vector $(\mathbf{x} - \mathbf{y})/r$, u_i is the i -component of the surface velocity vector, $M_r = u_i \hat{r}_i / c_0$ is the local Mach number in the source-observer direction, with c_0 the speed of sound.

The integral terms have to be evaluated at the emission time τ which, in the present case, is assumed equal to the observer time t . This assumption is valid since the rotational speed is much lower than the speed of sound and the source extension is such that the Maximum Frequency Parameter $MFP > 1$ (for details see [Cianferra et al. \(2019a\)](#)). A more detailed description of the propeller's acoustic compactness here considered is reported in [Cianferra et al. \(2019b\)](#).

The three surface integrals, referred to as linear terms, are associated with the noise generated by the rigid surface immersed in the flow. The first (thickness) term is related to the body motion, while the second and third terms (loading) are related to the unsteady pressure loads over the propeller blades. The volume terms evaluate the contribution of the fluid flow displaced by the body in the region surrounding the source. The primary contribution arises from the wake, where persistent turbulent flow structures develops. These terms are defined as non-linear. The present study focuses on the linear terms contribution only; thus, we evaluate the acoustic pressure through the FW-H equation (1) considering only the surface integrals. However, the non-linear terms can be retained and evaluated directly with the original FWH equation (Eq. 1). The analysis of the contribution given by the wake is currently under investigation and topic of a successive paper. In principle, the methodology remains the same as described in the flowchart in Fig. 1, apart the fact that the equation used to evaluate the source acoustic pressure in the second step is different. Specifically the noise reproduced by all terms of (Eq.1) must be considered. For the evaluation of the noise associated to the wake, for example, one can use the porous formulation proposed by [Di Francescantonio \(1997\)](#) or the more robust volume method discussed in [Cianferra et al. \(2019a\)](#).

2.3 Wave equation and FDTD

The acoustic wave equation (2) is solved with the FDTD method to obtain the acoustic pressure propagation in a three-dimensional medium, with variable

density and speed of sound:

$$\frac{1}{c(\mathbf{x})^2} \frac{\partial^2 p_{ac}^w(\mathbf{x}, t)}{\partial t^2} = \rho(\mathbf{x}) \nabla \left(\frac{1}{\rho(\mathbf{x})} \nabla p_{ac}^w(\mathbf{x}, t) \right), \quad (2)$$

where $c(\mathbf{x})$ is the speed of sound of the medium, p_{ac}^w is the acoustic pressure, $\rho(\mathbf{x})$ is the density of the medium. The equation is solved using a second-order in time and space explicit scheme.

The algorithm is stable when the following condition is satisfied:

$$\Delta t \leq (1/c^*) * (1/\Delta x^2 + 1/\Delta y^2 + \Delta z^2)^{-1/2}, \quad (3)$$

where c^* must be larger or equal to the maximum speed of sound in the medium. The physical meaning is that the information at each time step cannot travel further than the underlying grid cell. The Von Neumann stability analysis has been used to obtain this relation, which is valid for the second-order in the time and space explicit scheme. The stability condition imposes an upper bound on the time step of the simulation. Therefore it limits the maximum distance advanced by the acoustic waves at each time step. Different values of c^* in the interval $1500 \text{ m s}^{-1} - 2000 \text{ m s}^{-1}$ have been utilized with negligible differences in the results, enabling us to consider media other than water in the numerical domain without losing precision. For all the numerical experiments we use $c^* = 2000 \text{ m s}^{-1}$.

The boundary conditions have to be specified to solve the differential wave equation. Three different conditions can be implemented in general cases: the Dirichlet, the Neumann, and the open-boundary conditions. The Dirichlet boundary condition is applied at the water-air interface, where the pressure is set to zero. The effect is that all the acoustic energy is reflected into the domain with a phase shift of 180° (a discussion on this issue is in [Cianferra and Armenio \(2021\)](#)). The Neumann boundary condition is used to mimic the presence of perfectly reflecting walls, which are typically present in the marine environment at the bathymetric surfaces. Finally, the open-boundary condition, which allows mimicking an unlimited domain, is here implemented using a Perfectly Matched Layer (PML) ([Chern 2019](#)).

The PML is a region adjacent to the open boundaries of the numerical grid where the acoustic waves are damped out, which allows the avoiding spurious reflection in the numerical domain where the propagation of the acoustic signal is computed. We tested the implemented FDTD method ([Petris et al. 2022](#)) considering simple sources, like monopole, dipole, and quadrupole sources, for which analytical solutions are available. We found that the PML is very effective in canceling out spurious boundary reflections, primarily for homogenous media; in the case of a non-homogeneous medium, we observed very small spurious reflections, located at the interface between the two media (the case of a two-density medium was considered).

Two different methods can be used to implement the propeller signal: the *hard source* and the *soft source*, both of them discussed in (Petrís et al. 2022). These methods derive directly from room acoustics research, and the implementation details are described in Murphy et al. (2014). In this study, we consider the *hard source* method, as in Petrís et al. (2022). The source pressure is imposed as a time-varying Dirichlet boundary condition at specific grid nodes of the FDTD numerical grid, where equation (2) is not solved. In general this method is suitable for low-frequency sources. The main limitation of the *hard source* method is that the source nodes act as a perfect wall where the incident acoustic waves are reflected into the domain. However, this does not constitute a severe limitation in our applications. In fact, the source has a very limited physical extension compared to the propagation domain and to the main wavelength associated with the rotation frequency.

In the present paper the medium is considered quiescent and the source nodes are fixed in time; thus, the fact that the source moves with a constant velocity is not taken into account in the propagation of the acoustic wave. Although, in principle, the source velocity should be considered, due to the small propeller's advance velocity compared to the speed of sound and to the dimension of the propagation domain, our assumption of fixed source point does not introduce appreciable errors. In fact, in the canal case (Section 4) simulation's time window, the propeller advances less than 4 m in a domain 400 m long, where the speed of sound is 1500 m/s. Since the cell size is 1 m (see the next Section) this means that the propeller should have moved by four cells along the x -direction during the simulation. However, in order to arrive to a general methodology, the advance velocity of the body will be considered in the upcoming future.

2.4 FW-H and FDTD coupling

The essence of coupling the FW-H solution with the acoustic wave equation consists in using the FW-H acoustic pressure p_{ac}^{fwh} , evaluated at specific microphones, as a forcing term for the acoustic wave equation. The detail of the coupling is discussed hereafter.

The propeller is placed at the center (0,0,0) of the numerical FDTD domain, which has a constant grid spacing $\Delta x = \Delta y = \Delta z = 4D$, where $D = 0.25$ m is the propeller diameter. The schematic of the frame of reference together with the position of the propeller is depicted in Fig. 4. The propeller rotates counter-clockwise, and the wake develops along the negative x -direction.

The acoustic pressure is computed with the FW-H equation at the specific microphones illustrated as red dots in Fig. 4, also representing the grid nodes where the time-varying Dirichlet boundary conditions for the wave equation (*hard source* method) are imposed:

$$p_{ac}^w(\mathbf{x}, t) = p_{ac}^{fwh}(\mathbf{x}, t), \quad \mathbf{x} \in \Lambda, \quad (4)$$

where Λ is the ensemble of grid nodes illustrated as red dots in Fig. 4. The microphones where FW-H acoustic pressure is computed are chosen in such a way to correspond with the grid nodes of the FDTD. This approach avoids an interpolation procedure in space. The grid nodes that define the outer box vertexes are $(-6D, -6D, -6D) - (6D, 6D, 6D)$. The cubic box, where the grid nodes (microphones) are distributed, is large enough to retain the source's directivity. In this case, these grid nodes are the second nearest grid nodes from the source center; since in these nodes the acoustic wave equation is not evaluated but imposed as a forcing boundary condition, all the nodes within the box are not considered for the solution of the wave equation while the grid nodes outside the box the acoustic wave equation (Eq.(2)) is solved.

The rationale of this choice stands on the fact that the acoustic pressure gradient increases moving toward the source. Therefore, to evaluate the Laplacian correctly, two options are available: the first one is to increase the grid's spatial resolution which consequently increases the computational cost; the second one consists in applying the FW-H acoustic signals at grid nodes positioned at larger distances from the source, where the gradients of the acoustic pressure are less severe. Therefore, the choice of the dimension box has to be made to reach the following compromise: the box must be large enough to resolve the pressure gradient correctly and capture the directivity of the source correctly; the box has to be small enough to avoid spurious reflections in the presence of reflected waves (due for example to the free surface).

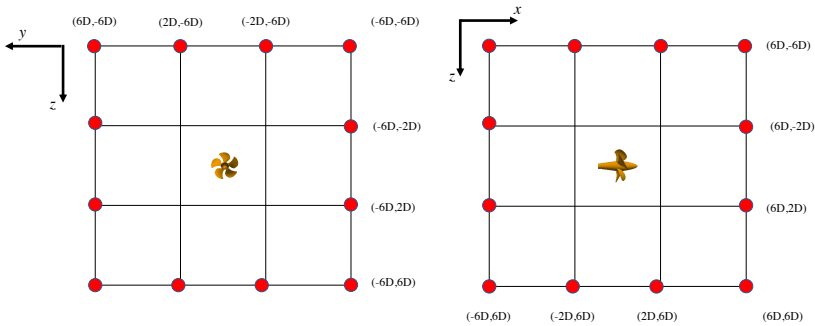


Fig. 4 Schematic of the grid nodes used to implement the propeller acoustic source on two different planes: left panel, $x = 2D$; right panel $y = 2D$. The *hard source* nodes are depicted in red.

Because of the LES computational cost, the available FW-H signal is limited to a period of $T = 0.8s$, corresponding to about 12 revolutions. Linear interpolation in time is needed since the time step of the FDTD is typically less than the interval between two consecutive available measures of acoustic pressure computed with the FW-H equation. In addition, the FDTD method requires a more extended signal since the acoustic field needs to reach a statistically steady-state before calculating the root-mean-square of the acoustic pressure.

The time needed to reach a steady state solution depends on the size of the domain. The recommended time window to collect the results obtained with the wave equation was found by Petris et al. (2022) to be at least three times the time needed by the waves to reach the most distant boundary from the source of the numerical domain. If the time required by the FDTD method exceeds the available FW-H time signal, it is extended by repeating a copy several times until the time required by the FDTD method is obtained. This procedure may introduce errors in the range of the highest frequencies, which may be out-of-phase when the signal is truncated. A comparison of the sound Spectrum Level (SL) of the original FW-H signal (limited to a period $T = 0.8\text{ s}$) and the same signal extended to $T = 2.4\text{ s}$ is shown in Fig. 5. The original signal has been collected at the point $(-6D, -6D, -6D)$ and the SL is evaluated as $SL = 20 \log_{10}(A/p_{ref})$, where A is the amplitude of the Fast Fourier Transform of the acoustic pressure p_{acs}^{fwh} and $p_{ref} = 1\mu\text{Pa}$. Fig. 5 shows no evident difference in the spectral content between the two acoustic signals. Moreover, it must be pointed out that the energy-containing frequencies are the lowest ($< 20\text{ Hz}$); consequently, the possible differences in the higher frequency ranges are of minor importance and can be neglected.

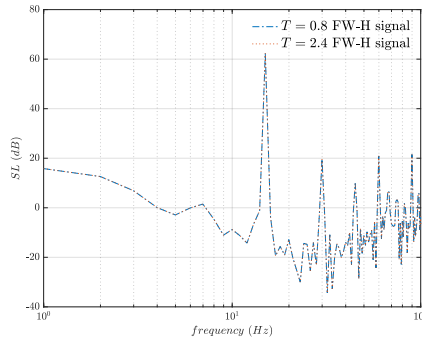


Fig. 5 Comparison of the original FW-H signal (labeled $T = 0.8\text{ s}$) and the same signal extended up to $T = 2.4\text{ s}$ at the point $(-6D, -6D, -6D)$.

3 Verification

The validity of the methodology herein proposed is evaluated by considering the case of a propeller in a unconfined and homogeneous medium and checking that the acoustic results in the far-field obtained by solving the wave equation are consistent with those obtained using the FW-H equation. Indeed, we point out that computing FW-H is equivalent to solving the wave equation in the case of unbounded and homogeneous domains.

We consider a homogenous infinite domain with $\rho = 1000\text{ Kg/m}^3$ and $c = 1500\text{ m/s}$. The FDTD domain is a square box, $404D$ (101 m) wide, and the cell's width is set to $4D$ (1 m). The open boundary conditions, applied in

all directions, ensure that the acoustic waves can leave the numerical domain without reflections. Accordingly, the numerical experiment mimics an infinite domain. The propeller is placed at the center of the domain $(0, 0, 0)$. The propeller axis is along the x -direction, the wake develops along the negative x -direction, and the propeller blade plane is over the y - z plane.

The linear terms of the FW-H equation (1), propagated with the FDTD method in Figures 6 and 7, generate an acoustic pressure that is not evenly distributed in space. A specific directivity pattern arises from these linear terms, and it is related to the rotation of the source, as evidenced by, among the others, Ianniello (2016). The linear terms of the FW-H equation generate most acoustic energy over the propeller blade plane, as evident from the comparison of Figures 6 and 7. In the Figures, the Sound Pressure Level (SPL) is used to evaluate the acoustic energy distribution in space and is calculated as $SPL = 20 \log_{10}(p_{rms}/p_{ref})$, where $p_{ac,rms}$ is the root-mean-square of the acoustic pressure p_{ac} , and $p_{ref} = 1 \mu Pa$. The numerical experiment is conducted for $8\hat{t}$, where $\hat{t}$ is time made nondimensional as $\hat{t} = t * V_0/D$, with $V_0 = 4 m s^{-1}$ the advance velocity of the propeller of the LES simulation and D the propeller's diameter. The results are then collected for $6\hat{t}$ starting from $2\hat{t}$. This time, $2\hat{t}$, is sufficient to enable the acoustic waves generated from the propeller to reach the furthest boundary. Then, the $6\hat{t}$ time window ensures that a statistically steady state is reached.

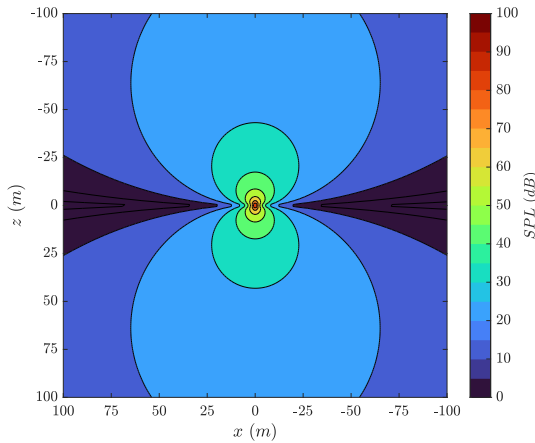


Fig. 6 Contour of sound pressure level of the marine propeller in the open-water case on the x - z plane at $y = 2D$, computed with the FDTD method.

Fig. 6 shows the SPL on the x - z plane with an offset of $2D$ ($0.5 m$) in the y -direction. The plane passing through the propeller axis is not available since the propeller is located at the center of the grid cell (see Fig. 4). This holds for all numerical experiments herein discussed. The linear terms do not contribute to the acoustic energy along the propeller axis (x -direction) since the SPL decays rapidly below zero in this direction. Indeed, in this plane, the

acoustic energy exhibits an axial-symmetrical dipole-like pattern. Fig. 7 shows that the SPL in the y - z plane passing through $x = 2D$ is axisymmetric. Consequently, the acoustic pressure is evenly distributed in these planes. The combined analysis of Fig. 6 and Fig. 7 shows that a large part of the acoustic energy is contained in the y - z planes close to the propeller.

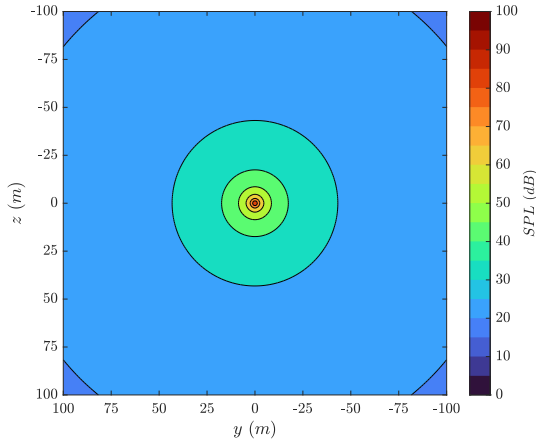


Fig. 7 Contour of sound pressure level of the marine propeller in the open-water case on the y - z plane at $x = 2D$, computed with the FDTD method.

In Fig. 8 we compare the acoustic pressure computed through the FW-H equation (1) with that obtained with the methodology proposed in this paper. The analysis is made by comparing the signals along the y -line $x = 2D$, $z = 2D$ contained in the y - z plane since it contains the most acoustic energy. The results from the FW-H equation are labeled FW-H, and the results from the wave equation are labeled WAVE. The acoustic pressure evaluated with the FW-H method is recorded at probes positioned every $4D$ ($1m$) between $6D$ ($1.5m$) and $42D$ ($10.5m$) and then every $40D$ ($10m$), along the y -direction. The acoustic pressure evaluated with the FDTD method is recorded at the same points reported above, along the y -direction. It is collected for $8\hat{t}$ for both methods, and then the quantity p_{rms} is evaluated. The decay of the SPL is the same for both method, and the relative error is below 1% at all probes.

The pressure signal is then evaluated at a single probe, placed at $(2D, 202D, 2D)$ from the source to verify that the acoustic pressure's spectral component is propagated correctly. The comparison between the SL of the two signals obtained with the two methods is shown in Fig. 9. The results are shown up to $100Hz$ since the FDTD method has a limitation on the maximum frequency which can be propagated without dispersion error, as discussed in Petris et al. (2022). However, since most of the acoustic energy generated by marine propellers is concentrated in a low-frequency range, the FDTD method is suitable for this purpose. The coupled method correctly reproduces

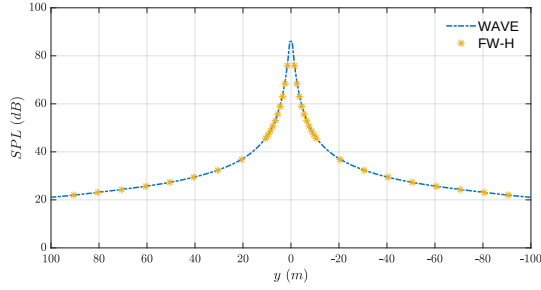


Fig. 8 Comparison of sound pressure level on the line $x = 2D$, $z = 2D$ evaluated with the FW-H equation (FW-H) and with the wave equation (WAVE) for an unbounded domain and homogeneous medium.

the peak frequency at 15 Hz , which corresponds to the propeller's revolution frequency ($n = 15\text{ rps}$), and the relative error between the two amplitudes is less than 1.5%. The secondary peak that typically occurs at blade frequency nN is not observed in this case, due to the distance from the source. Indeed, it is observable in the acoustic near-field up to few diameters ($\sim 6D$, see Fig. 5 and (Cianferra et al. 2019b)). The low-frequency region is similar between the two methods, and only minor discrepancies in the high-frequency region are observed.

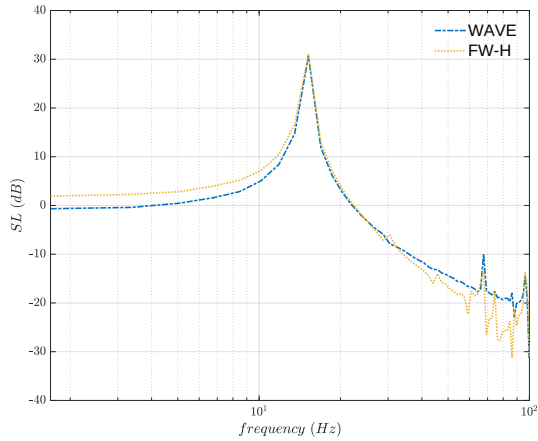


Fig. 9 Sound spectrum level of the marine propeller evaluated with the FW-H equation (FW-H) and the wave equation (WAVE) at the point $(2D, 202D, 2D)$ for an unbounded domain and homogeneous medium.

4 Propeller noise propagation in a confined canal

In this section, the coupled method is used to evaluate the propagation of the propeller-generated noise in a confined, realistic environment. Here, we analyze sound propagation in a canal that exhibits interesting differences from the open-space case.

The domain considered herein is a simplified perfectly reflecting canal with a free surface at the top boundary. The canal is $200D$ ($50m$) deep, $412D$ ($103m$) wide and $1612D$ ($403m$) long. Along the x -direction open boundary conditions are imposed, mimicking a canal infinite in length.

The analysis conducted is devoted to quantifying the effect of confinement on the composition of direct and reflected acoustic waves generated by the propeller. Therefore, the dimension of the channel is not crucial for the main scope of our research. However, we may note that the dimensions we have chosen are comparable with those of the Suez Canal which has a depth of $\simeq 25m$, a width of $\simeq 300m$ and a length of the order of tens of kilometers.

At $z = 0$ we set the free surface boundary condition $p = 0$, mimicking the interface between water and air. At $z = 200D$ ($50m$), the bottom wall is considered as a perfect reflecting surface so as the two lateral boundaries, and it is obtained by imposing the Neumann boundary condition. This can be considered an approximation of the reflection occurring at the interface between water and a medium much denser than water. The water has a constant density ($\rho = 1000 Kg/m^3$) and speed of sound ($c = 1500 m/s$). As in the previous case, the numerical experiment is conducted on a grid with a cell's width of $4D$ ($1m$) and in a time window of $8\hat{t}$. Then, in order to compute the root-mean-squares, the acoustic pressure is collected in the time interval $2\hat{t}$ – $8\hat{t}$. The propeller and the coupling procedure are the same as described in the previous section. The propeller in this numerical experiment is located at the center of the canal at a depth $22D$ ($5.5m$). It is representative of an underwater vehicle passing through the canal.

The acoustic pressure signal imposed at the nodes of the FDTD is the superposition of the direct and image signal computed with the FW-H equation. With the image method applied to the FW-H equation through the use of the half-space Green function, we consider the reflected waves by the nearest boundary to the source, in our case, the free surface. In [Petris et al. \(2022\)](#), the authors showed that with the *hard image* method, which considers the source signal as the composition of direct acoustic waves and reflected ones from a free surface, a more accurate estimate of the propagated acoustic field is obtained.

In [Fig. 10](#) we show the contour of the SPL of the marine propeller in the canal case, extracted on plane $y = 2D$, close to the propeller axis. The characteristic dipole-like pattern observed in [Fig. 6](#) for the open-water case is still observed in this case with substantial differences; the main difference is lack of symmetry with respect to the horizontal plane containing the axis of the

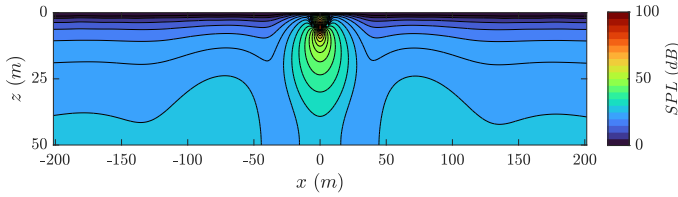


Fig. 10 Contour of sound pressure level of the marine propeller in the canal case on the x - z plane at $y = 2D$, computed with the FDTD method.

propeller, due at large extend to the presence of the free surface and, also, to the presence of the lateral walls. The zero sound emission line, namely the propeller axis in the open water case, is now bent towards the free surface. A shadow zone, meaning an insonified region of the domain, is noticed along the free surface and spans the whole channel's length, deepening with the distance from the source. This shadow zone is the result of scattering of the acoustic waves incident on the free surface (Harrison 1979; Jensen et al. 2011). The SPL is symmetric along the x -direction, whereas regions of higher and lower SPL are identified on the plane. In particular, a region of increased SPL is observed attached to the bottom from about $200D$ ($50m$) to the end of the channel due to bottom reflections. A region of lower SPL is observed between this region and the source, spanning from the free surface to the bottom wall. These effects result from the superposition of different acoustic waves reflected from the domain boundaries. Indeed, the canal's acoustic energy is constrained inside the canal compared to the open-water case, as shown in Fig. 11.

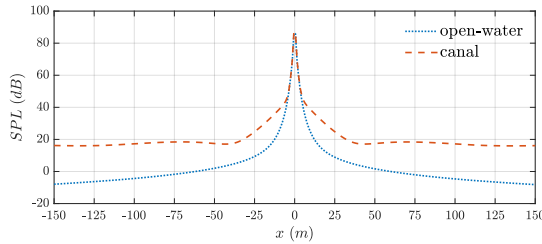


Fig. 11 Comparison of the sound pressure level of the marine propeller in the canal case and the open-water case along the line $y = 2D$, $z = 2D$, computed with the FDTD method.

Specifically, in Fig. 11, we compare the SPL of the marine propeller, in the canal case and in the open-water case, computed along the line $y = 2D$, $z = 2D$. In the open-water case, the SPL monotonically decays below zero because the decay of the acoustic pressure is governed by the geometrical spreading of the acoustic waves. This not holds in the canal case, where three different rates of decay of SPL with the distance from the source are detected: in the very near field, the decay rate is the same as in the open-water case; the difference appears precisely at a distance equal to the depth of the source. This is because the spherical spreading of the acoustic waves is interrupted

by the presence of the free surface and resulting reflection. Moving farther, the decay rate changes and remains constant almost up to the distance from the bottom, $178 D$ ($44.5 m$); even farther from the source, the acoustic energy remains constant along the canal's length since it is trapped inside the canal by the lateral and bottom walls and by the free surface. The change of decay appears mostly related to the presence of the upper and lower horizontal walls, whereas the nearly constancy of the signal in the far field has to be associated to the confinement of the acoustic signal in the cross-stream plane.

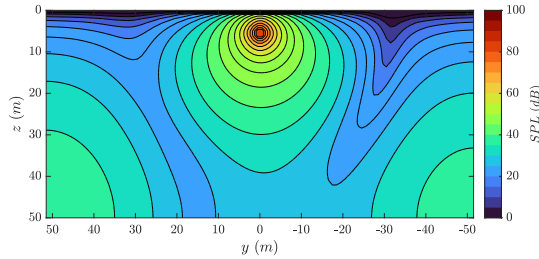


Fig. 12 Contour of sound pressure level of the marine propeller in the canal case on the y - z plane at $x = 2D$, computed with the FDTD method.

The presence of the four boundaries affects the distribution of acoustic energy also over the blade's plane, as shown in Fig. 12, where the contour of SPL of the marine propeller in the canal case is shown on the plane $x = 2D$. Similar to the x - z plane, regions of relative maxima and minima of SPL are identified. At the bottom corners, large maxima of SPL are observed, but the SPL level is not the same at the two corners since the distribution of the acoustic energy is not symmetric with respect to the plane $y = 0$, where the propeller is located. This aspect is discussed further in Section 5. Between the corners and the source, a zone of minimum SPL at an angle of 53° to the bottom is observed. As discussed, the inhomogeneity of the SPL is due to the superposition of the acoustic waves reflected by the boundaries. [Da Costa Campos et al. \(2021\)](#) examined these effects for a very simple configuration; specifically, the authors provided a framework to evaluate the impact of a simple corner boundary on the acoustic field generated by a monochromatic monopole. We extend the mentioned work to highlight that the geometric characteristics of the domain are essential to understand the acoustic response for more complex cases. The total acoustic pressure at a point close to a corner is obtained as

$$p_{tot} = F p_{dir} = F \frac{1}{r} \exp(ikr), \quad (5)$$

where p_{tot} is the total pressure, F is the multipath factor, p_{dir} is the pressure of an open-water monopole, $k = 2\pi/\lambda$ is the wavenumber with λ the wavelength of the source, and r is the distance from the source. The multipath factor F

is then evaluated as (Da Costa Campos et al. 2021):

$$\begin{aligned}
 F = & 1 + R_h R_v \frac{q-s}{q+s} \exp(i2ks) + \exp[ik(s-q)] \\
 & \times \left\{ R_h |\cos^2 \alpha + \left(\frac{q-s}{q+s}\right)^2 \sin^2 \alpha|^{-1/2} \right. \\
 & \times \exp\left(ik\sqrt{(q+s)^2 \sin^2 \alpha + (q-s)^2 \cos^2 \alpha}\right) \\
 & + R_h |\sin^2 \alpha + \left(\frac{q-s}{q+s}\right)^2 \cos^2 \alpha|^{-1/2} \\
 & \left. \times \exp\left(ik\sqrt{(q+s)^2 \cos^2 \alpha + (q-s)^2 \sin^2 \alpha}\right) \right\},
 \end{aligned} \tag{6}$$

where R_h and R_v are, respectively, the reflection coefficients of the horizontal and vertical wall, that constitute the corner ($R_h = 1$ and $R_v = 1$ in our case), q is the distance of the source from the corner, s is the distance of the corner from the observer (the distance from the source to the observer is then $r = q - s$), and α is the angle between the observer and the horizontal wall ($\alpha = 0.722 \text{ rad}$ in our case). In our case, the multipath factor F is function of the distance between the source and the observer only.

Here, we consider a monopole with $k = 0.0628 \text{ m}^{-1}$, which corresponds to a pressure signal oscillating at the revolution frequency of the propeller (15 Hz), positioned at the same distance from the corner as the propeller in the canal case. We refer to this case as the *Ideal Corner Case*. In Fig. 13 we compare the $p_{ac,rms}$ computed through equation (5) with that obtained using the FDTD method, considering both the canal case (Fig. 12) and the ideal corner case. Pressure is computed along a straight line connecting the source with the corner from $kr > 0$ to $kr = 4.27$, where r is the distance from the source.

The ideal corner case mimics the case computed with Eq.(6), but is obtained by solving the acoustic wave equation with the FDTD. Therefore Neumann boundary conditions are imposed at the lateral walls that constitute the corner, while all other boundaries are treated as open. The $p_{ac,rms}$ is then collected in a time window sufficient to reach a steady state, and the grid cell dimension is 1 m .

As expected, the multipath factor and ideal corner case $p_{ac,rms}$ mostly overlap. Minor differences are observed near the minimum and near the source. The differences can be attributed to the assumption utilized in the evaluation of the multipath factor and the fact that the line in the ideal corner case is interpolated from the results over the numerical grid. Nevertheless, the location of the minimum of $p_{ac,rms}$ is correctly computed. We point out that the minimum of the $p_{ac,rms}$ of the canal case is located at the same distance as

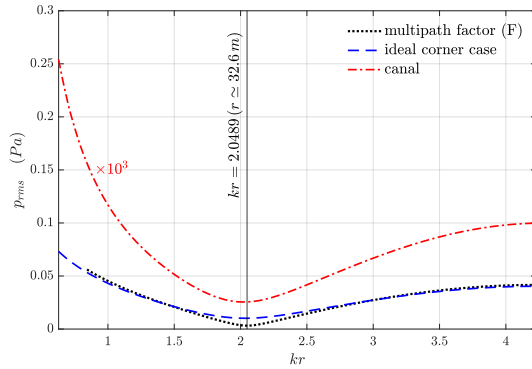


Fig. 13 Comparison of the $p_{ac,rms}$ along the line connecting the source and the corner from $kr > 0$ to $kr = 4.27$ computed with equation (5), and the FDTD method in the ideal corner case and the canal case. The $p_{ac,rms}$ of the canal case is multiplied by a factor of 10^3 .

the other two cases. A contour plot of the SPL, in Fig. 14, shows the acoustic field in the two cases, ideal corner case and canal case. The location of the minimum is highlighted with a dashed line.

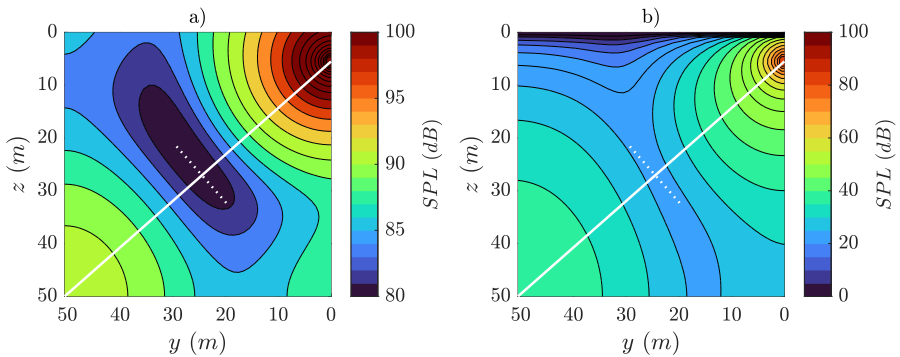


Fig. 14 Contour of SPL of the ideal corner case a) and the canal case b) (Fig.12). Equation (6) is evaluated along the white line and the intersection with the perpendicular dashed line represents the position of the minimum at $kr = 2.0489$ (≈ 32.6 m) from the source.

The multipath factor F formula represents a simpler case than the canal case since it does not consider all the others reflecting boundaries and a source with a specific directivity pattern. In spite of the simplification, the multipath factor F exhibits a minimum of pressure at a distance of about $kr = 2.0489$ (≈ 32.6 m) and a relative maximum close to the corner, similarly to the canal case. This simple analysis clearly shows that the presence of the corner definitely affects the acoustic energy distribution, and justify relative minima of SPL, as observed in Fig. 12.

A relative minimum is then also clearly identified in Fig.15, where a comparison of the SPL of the marine propeller in the canal case and the open-water

case, computed along the line $x = 2D$, $z = 2D$ (the source depth), is shown. In Fig.15 we observe that two cases share the same decay near the source, up

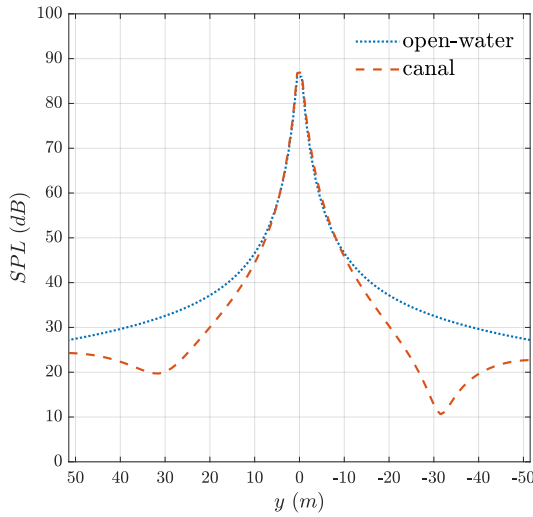


Fig. 15 Comparison of the sound pressure level of the marine propeller in the canal case and the open-water case along the line $x = 2D$, $z = 2D$, computed with the FDTD method.

to a distance equal to the depth of the source $22D$ (5.5 m). Then, relative minima are observed in both positive and negative y -direction at approximately $124D$ (31 m), where a clear asymmetry is detected. At the edges of the canal, an increase of SPL is observed. For the canal case, the measured SPL on the blade plane is lower than in the open-water case, and apparently this is in contrast with Fig. 11, which shows that the SPL of the canal case is always greater than the open-water case. This occurs because less energy is transmitted in the blade plane for the canal case due to the boundedness of the cross sectional area, and most of the reflected energy is propagated along the canal's length. In this sense, the boundedness of the cross sectional area provides the only direction of propagation of the acoustic signal over the unlimited dimension.

In Fig.16 we compare the spectra of the acoustic signals, regarding open-water case and canal case, evaluated at the point $(2D, -126D, 2D)$, where the absolute minimum of sound pressure level of Fig. 15 is observed. The SL is evaluated from a pressure signal collected for $12\hat{t}$. The numerical experiment has been extended only to collect the acoustic pressure at this microphone to obtain more data for the Fourier Transform analysis. The boundedness of the domain dramatically modifies the signal, the main differences between the two cases being the complete absence of the primary peak frequency at 15 Hz and the damping of the pressure signal in the low-frequency range. To be noted that the low frequencies are those primarily affected by the boundaries, whereas the high frequency part of the signal feels the boundaries as placed “in the far field”.

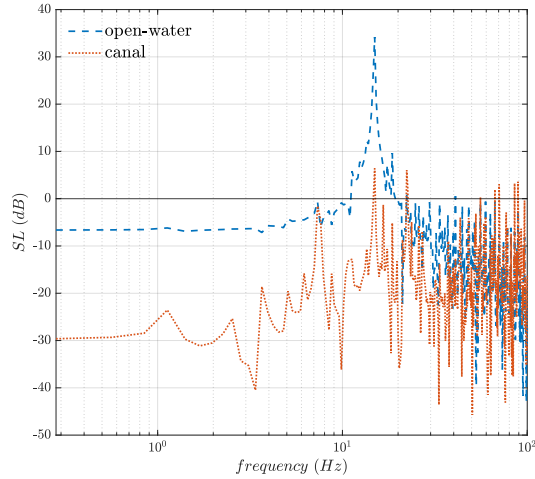


Fig. 16 Comparison of the sound spectrum level of the marine propeller in the canal case and the open-water case along the line $(2D, -126D, 2D)$, computed with the FDTD method, where the absolute minimum of sound pressure level of Fig. 15 is observed, computed with the FDTD method.

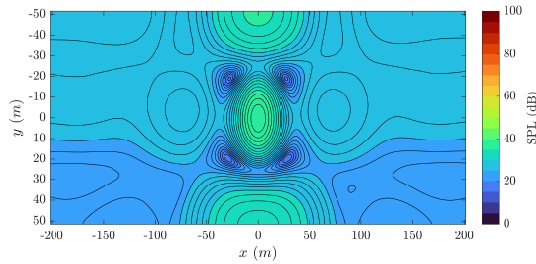


Fig. 17 Contour of sound pressure level of the marine propeller in the canal case on the $x-y$ plane at $z = 104D$, computed with the FDTD method.

Regions of minima of SPL other than those discussed above are present in other regions, as highlighted in Fig.17, where the contour of SPL of the horizontal plane at $z = 104D$ ($26m$) depth is shown. Four minimum SPL spots are located at the corner of a square of $100D$ ($25m$) side, enclosing the propeller's horizontal position, creating a region of insonification in this particular case. The distance at which the insonification occurs is comparable with the relative minimum evaluated with equation (5), and these effects are related to the presence of the lateral walls. It is clear that the effects are related to the lateral wall since, since in Fig. 11 we do not observe the presence of a minimum along the $x - direction$. Compared to the $y-z$ plane, where the path of the direct and the multiple reflected acoustic waves are analyzed on the same plane, in the $x-y$ plane, the multiple reflected waves lay on different planes than the one connecting the source and the minima. Consequently, an analytical estimation of a correct multipath factor is more complicated. Then,

along the y -direction, a higher SPL near the lateral walls is observed, as in Fig. 12. The asymmetry of the SPL along this direction is even more evident.

In conclusion, the presence of boundaries generates strong inhomogeneity of the acoustic field compared to the open-water case.

5 Symmetry breaking rotating acoustic source

Within an unbounded domain, it is impossible to determine the rotor's direction of rotation by measuring the acoustic field of a rotating source at a single point in space. A rotor that turns clockwise or counterclockwise with respect to the single observer will produce the same acoustic field. As observed in Fig. 7, the acoustic energy is perfectly symmetric in any plane orthogonal to the propeller axis. However, if a free surface bounds the propagation domain the symmetry is broken. We perform an additional simulation, considering the presence of the free surface while considering all other boundaries open. In this case the marine propeller is placed $22D$ (5.5 m) below the free surface as in the previous case and the acoustic pressure has been collected in the time window $2\hat{t} - 8\hat{t}$. The effects of the free surface are evident in Fig. 18, where we show the contour of SPL, on the plane $x = 2D$, which corresponds to a location upstream the propeller.

The effects of the free surface on the acoustic field, *i.e.* the asymmetry, are independent of the hydrodynamics effects that would occur if the propeller were placed in the proximity of the surface. Indeed, at the depth considered, the hydrodynamics of the propeller is not affected by the free surface, and the open-water condition of the LES simulation is valid.

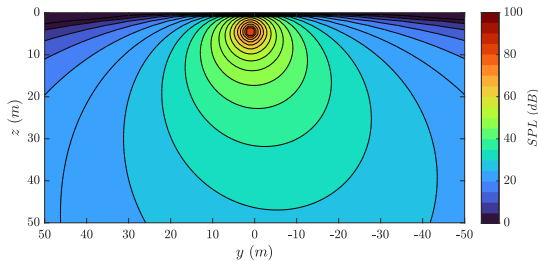


Fig. 18 Contour of sound pressure level of the marine propeller in the free surface case on the y - z plane at $x = 2D$, computed with the FDTD method.

In the SPL contour, the shadow zone near the free surface is present as in the canal case, but a clear asymmetry of the acoustic energy distribution in the plane is detected. The propeller turns counterclockwise, and an increase of SPL is observed in the direction of the fourth quadrant of a frame of reference centered at the propeller axis.

The asymmetric distribution of the acoustic energy was also verified by placing the propeller near the bottom; the latter was treated as a free surface. In this case, an increase in SPL was observed in the direction of the

second quadrant. (The results are not shown). Consequently there is a relation between the direction of rotation and the free-surface location.

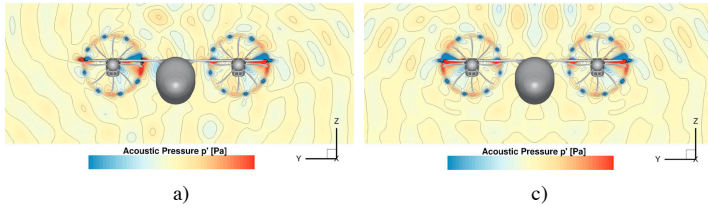


Fig. 19 Instantaneous unsteady pressure field visualization in the transversal plane at $\sim 1R$ behind the propeller plane for a) co-rotating and b) counter-rotating top-in propellers. Figures taken from [Chirico et al. \(2018\)](#). Courtesy of [Chirico et al. \(2018\)](#).

An asymmetry of the acoustic pressure field is also observed in Fig. 19 (Figure 8 in [Chirico et al. \(2018\)](#)), where the authors showed the acoustic field generated by two top-in propellers, which are co-rotating in Fig. 19 a) and counter-rotating in Fig. 19 b). This latter condition mimics our experiment, where a vertical plane passing through the airframe center replaces the role of the free surface. In Fig. 19 a), the acoustic pressure is asymmetric with respect to the airframe plane. The asymmetric acoustic pressure distribution in the space is related to the different directions of rotation of the blade relative to the airframe (direction of rotation of the marine propeller with respect to the free surface in our case). On the other hand, in Fig. 19 b), the propellers rotate specularly with respect to the airframe, producing the same reflected field. In Fig. 19 c) the asymmetry is clear also with respect to the z - direction, as in our case (Fig. 18). Indeed, the two propellers of Fig. 19 c) can be interpreted as the real and the imaginary sources, where one is a mirror reflection of the other.

In order to further verify the correctness of the methodology, we evaluate the asymmetry using the FW-H equation (Eq.1) and compare it with the results obtained with the wave equation.

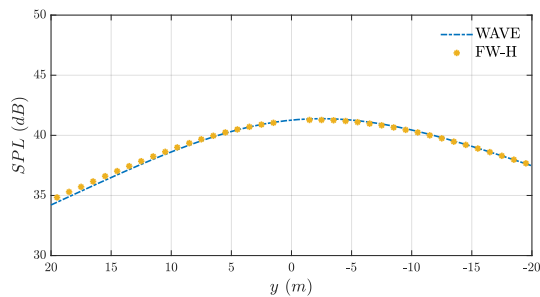


Fig. 20 Comparison of the sound pressure level of the marine propeller in the free surface case on the line $x = 2D$, $z = 84D$ between the FW-H equation and the wave equation (WAVE)

In Fig. 20, the comparison of SPL between the FW-H equation (label FW-H) and the wave equation (label WAVE) is shown on the line $x = 2D, z = 84D$. The FW-H results are obtained using the method of the image. The imaginary source is equivalent to a propeller which rotates in a specular way with respect to the real one. The two methods show the same asymmetry across the y -direction, confirming the ability to use the wave equation instead of the image method to obtain correct estimate of the noise propagation. The SPL difference at the two opposite point of the line, see Fig. 20, at about $y = \pm 20m$, is of 3 dB . A minor difference is observed between the FW-H equation and the wave equation, however the maximum relative error is less than 1%.

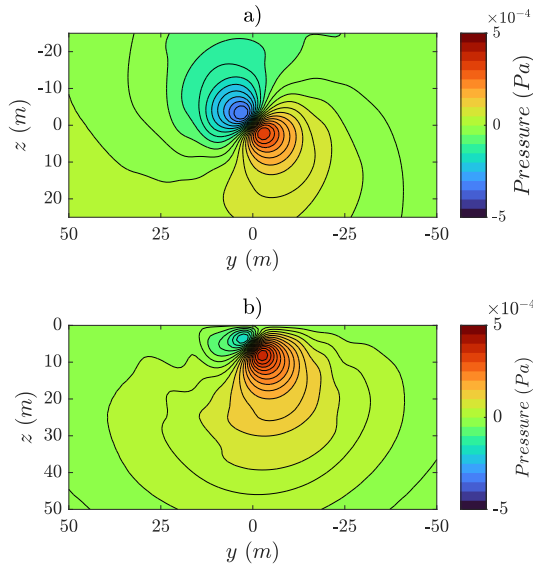


Fig. 21 Acoustic pressure of the marine propeller on the plane $x = 2D$ relative to the source position: a) *open water case* b) *free surface case*, computed with the FDTD method.

We show in Fig. 21, a snapshot of the acoustic pressure of the marine propeller on the plane $x = 2D$ for the *open water case* (a) and the *free surface case* (b). In both cases, the range of acoustic pressure is limited in the range from $-5 \times 10^{-4} \text{ Pa}$ to $5 \times 10^{-4} \text{ Pa}$ to better highlight the acoustic pressure far from the source. Results are shown at the same time instant from the start of the simulation. In the *open water case*, Fig. 21 a), the dipole-like pattern of the acoustic waves is clear near the source. Two lobes with an opposite value of pressure are identified. Far from the source, the pressure level lines bend, assuming the shape of a spiral, following the propeller's rotation. At this distance from the source, in the acoustic far-field, we cannot visualize the acoustic waves originating from the single blades but only a superposition of acoustic waves, which give rise to a signal characterized by the revolution frequency. In the near field, as discussed by Chapman (1993), it is possible

to visualize the transition from the near field (blade region) to a intermediate field, where the shape of the acoustic waves still “remember” the blades.

The free surface breaks the spiral symmetry of the acoustic waves, Fig. 21 b). The two lobes of the dipole pattern are still present, but they do not have the same shape as in the unbounded domain. At this instant, the positive pressure lobe is similar to Fig. 21 a), while the free surface affects the negative pressure lobe, deforming it compared to the unbounded domain case. So in the vicinity of the reflecting surface, negative and positive pressure lobes deform, alternating with the rotation. Indeed, the dipole-shaped pressure field rotates following the rotation of the propeller. The acoustic wave’s wavefront, impacting the free surface, generates the asymmetry of the acoustic pressure field.

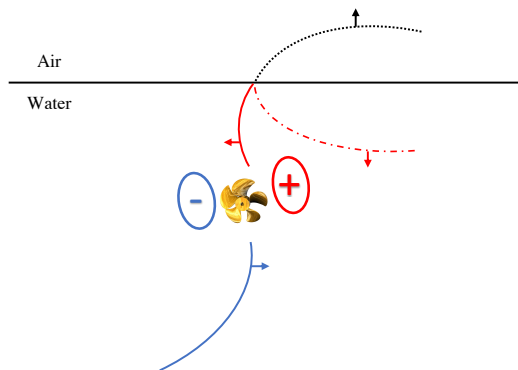


Fig. 22 Schematic of the acoustic pressure field of Fig.21. The propeller is rotating counterclockwise, and we observe the figure from upstream.

It is easier to understand the phenomenon from Fig. 22, where we show a schematic of Fig. 21. The two wavefronts generated from the dipole are displayed with a solid line, and as the propeller rotates, the normal of the wavefront turns toward the direction of rotation. The dotted black line in the air region represents the wavefront if the free surface was absent, as in Fig. 21 a). In this case, the wave’s wavefronts are symmetric, and the overall acoustic pressure field is symmetric, as observed in Fig. 7. If the interface between air and water is present, the wavefronts impact the interface always from the right side of the Figures 21 and 22. Then, the reflected acoustic wavefront, displayed in a dash-dotted red line, consistently originates from the right side. The superposition of the reflected wavefront and the direct one, which is continuously generated by the rotation of the two-lobes pressure field, leads to an increase in acoustic pressure on the right side of Fig.21 (b). Therefore, more acoustic energy is observed in the negative y-direction of Fig. 18 or Fig. 21 b).

6 Conclusion

In the present paper, we develop a methodology for evaluating the noise propagation of an arbitrary source in confined domains. The methodology is composed of three main steps: in the first two steps the acoustic analogy is applied which uses a CFD hydrodynamic solution together with the integral form of the FW-H equation to characterize the noise source; as third step the methodology solves the wave equation in the physical domain, using the acoustic solution obtained with the FW-H equation as forcing boundary conditions. The methodology couples the advantages of the acoustic analogy with the flexibility given by the wave equation, which allows to calculate the noise propagation in a realistic domain, characterized by the presence of boundaries and fluid inhomogeneity. The implementation of the acoustic signals obtained by means of the FW-H equation in the wave equation is carried out using the hard-image method already discussed in [Petris et al. \(2022\)](#), particularly suited when a free surface is present. Although the methodology is of general use, here it is applied to a marine propeller, whose fluid-dynamic field and acoustic characterization were discussed in [Cianferra et al. \(2019b\)](#). Verification of the methodology has been carried out in open-water conditions and in presence of a water-air interface. We successively study the case of a propeller emitting noise in a canal, bounded by the free surface and by three reflecting walls, namely lateral and bottom surfaces. It is shown how the boundaries in the marine environment largely affect the propagation of acoustic waves. The noise distribution loses the typical shape that characterizes the open water case and exhibits a complex pattern with local minima and maxima, depending on the combination of direct and reflected waves. The spatial decay of the acoustic field is similar to that of the open water case in the near field only; with increasing distance from the source, the decay rate changes, and the change of slope occurs at specific distances from the source related to the distance of the source from the boundaries and to the dominant wave lengths.

The rotation of the propeller, combined with the presence of the free surface, gives rise to an asymmetric distribution of the acoustic signal over the planes parallel to the propeller axis. This is attributed to the fact that rotation modifies the composition of the direct and reflected waves increasing the overall signal by one side of the propeller.

The results of this study may be helpful for the analysis of signals propagated in real-scale confined regions, as well as for the analysis of laboratory-scale experiments carried out in water tunnels.

Finally, we highlight the fact that the present methodology in the upcoming future will be improved in several aspects. Specifically, the present work focuses on the linear part of the FW-H equation, not including the non-linear terms representative of the noise produced by the wake; also, the propeller displacement is not considered in the propagation model. Considering the contribution of the wake poses additional modeling issues and will be addressed in the future, along with a more realistic scenario, where density and speed of sound variations are addressed. In addition, more work on the proposed

methodology is needed to address the propeller's forward motion. This aspect may be relevant in case of high speed marine vehicles.

Finally, regarding ship propellers, an important aspect is the possible occurrence of cavitation, which enhances the production of noise. This aspect will be handled in the first two steps of the presented methodology, i.e., the fluid flow simulation and the subsequent application of the FW-H equation. The third step, i.e., coupling with the acoustic analogy and propagation model, remains valid as it is.

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