Numerical prediction of ship propeller noise through acoustic analogy

Marta Cianferra¹, Andrea Petronio², Vincenzo Armenio¹

¹Dipartimento di Ingegneria e Architettura, Units, Trieste, Italy
²IeFluids S.r.l., Trieste, Italy

ABSTRACT
This work presents a numerical computation of the acoustic field generated by an isolated marine propeller, in open water conditions. The propeller considered corresponds to a benchmark case, for which fluid dynamic data are available in literature and online. The fluid dynamic field, which represents the source of noise, is reproduced through a Large Eddy Simulation, the small scales of motion are modeled through the dynamic Lagrangian model and a wall-layer model allows to avoid the resolution of the viscous sub-layer. The acoustic field is reconstructed by the Ffowcs Williams and Hawking equation, which is composed of surface and volume terms indicating different noise generation mechanisms. By isolating each term contribution is shown that the shaft vortex constitutes a considerable source of low frequencies noise.

Keywords
Hydroacoustics, isolated propeller, Large-Eddy Simulation, Ffowcs Williams and Hawkins.

1 INTRODUCTION
The regulation for noise emission from marine vehicle, in protected sea regions, is becoming more stringent, allowing for the transit only to certified silent ships [8]. The development of new generation noise prediction tools is thus required for the correct design of ship. Nowadays, high-resolution unsteady and eddy-resolving numerical simulation of the turbulent field around a full-scale ship propeller is becoming computationally affordable as well as the hydrodynamic noise prediction which is now at hand. In the present work we focus on an isolated marine propeller, that may be considered among the major sources of underwater noise. The Ffowcs Williams and Hawking (FWH) analogy represents a powerful tool able to reconstruct the acoustic field, using numerical fluid dynamic data describing the development of the noise source. The FWH analogy, applied to a marine propeller, considers two noise generation mechanisms: the first one is related to fluid-structure interactions and depends on the propeller shape and rotational velocity, it generates a tonal noise, prevailing in the near field; the second one comes from vortices coherent structures propagating downstream. Although the first effect has been well recognized in the past and evaluated through the use of simplified models, the second one has been usually neglected due to inherent difficulties in both the accurate evaluation of the wake and in the computation of the volume terms of the FWH equation.

In recent literature the fluid dynamic and acoustic analysis of a marine propeller has been carried out by a number of authors. Among the others, Di Mascio et al. (2014) performed detached eddy simulations (DES) of a propeller placed in oblique flow; the authors adopted a grid of about $11 \times 10^6$ cells, and observed a very complex vortical system composed of a strong tip vortex, less intense trailing vortices due to the variation of the loading, different blade root vortices and an intense hub vortex. Di Felice et al. (2009) carried out both experimental and numerical (LES) tests of a submarine propeller. Their fine mesh simulation, composed of about 4.5 millions cells gave results in agreement with data obtained in laboratory. Chase & Carrica (2013) performed RANS, DES and Delayed DES (DDES) of a submarine propeller, adopting four different grids. The authors concluded that the grid refinement has weak effect on thrust and torque evaluation, still being important for the accurate reproduction of the wake dynamics. The very recent massive simulations of Balaras et al. (2015), Kumar & Mahesh (2017) and Posa et al. (2019) stand at the edge of the computational cost. The former carried out a wall-resolving LES of a propeller in open-water conditions and in the presence of an upstream appendage at zero incidence, to deal with a realistic configuration. Kumar and Mahesh performed high resolution wall-resolving LES using more than 180 millions of grid cells, validated their results with experimental data and reported a wide and deep analysis on the fluid dynamics of the propeller. In the work of Posa et al. (2019) LES results are validated against PIV measurements, the authors adopts the immersed boundary method with a cylindrical Eulerian grid composed of about 840 million nodes. These recent studies clearly show the advantage of considering eddy-resolving methodologies in contrast to RANS.

In this study, the hydrodynamic field is carried out through Large-Eddy Simulations (LES), solving the incompressible form of the filtered Navier-Stokes equations. The small and dissipative scales of turbulence are parametrized using a dynamic Lagrang-Stokes equations. The small and dissipative scales of turbulence are parametrized using a dynamic Lagrang-Stokes equations. In order to work with an handy grid, a wall model was adopted, instead of resolving the viscous layer. However, the grid is fine in the wake region to allow an adequate resolution of the coherent structures, necessary for the acoustic analysis. As a post-processing of the LES data, the integral FWH is solved, and the contribution of the linear and non linear terms of the FWH equation are investigated and discussed.

2 NUMERICAL MODEL
The problem under investigation is axial-symmetric, with a constant rotation rate. Under these conditions the governing equations can be recast in the rotating non-inertial frame of reference, thus adding the body forces accounting for rotational effects. The incompressible filtered Navier-Stokes equations are then formulated as suggested in Kumar & Mahesh (2017), with the Coriolis and centrifugal body-forces that take into account the rotational effects, along with the continuity equation:

$$\frac{\partial \Sigma_i}{\partial t} + \frac{\partial}{\partial x_j} (\Sigma_i \Sigma_j - \bar{u}_i \epsilon_{jkl} \omega_k x_i) = \frac{1}{\rho_0} \frac{\partial \Sigma}{\partial x_i}$$

(1)

$$+ \nu \frac{\partial^2 \Sigma_i}{\partial x_j \partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j} - \epsilon_{ijk} \omega_l \Sigma_k,$$

$$\frac{\partial \Sigma_i}{\partial x_i} = 0,$$

(2)

where the overbar denotes a filtered quantity, $u_i$ denotes the fluid velocity along the $x_i$ direction, $t$ is time, $\rho_0$ and $\nu$ are respectively the fluid density and kinematic viscosity, $p$ is the hydrodynamic pressure, $\epsilon_{i,j,k}$ is the Levi Civita III-order tensor, $\omega_i$ is the $i$-component of the rotation vector and $\tau_{ij}$ is the SGS stress tensor. Filtering is necessary in LES to separate the resolved fluctuating field from the unresolved one, whose parameters are parametrized through the SGS model. Here we use a dynamic Smagorinsky model, with the constant averaged along the Lagrangian trajectory of the fluid particles (Meneveau et al 1996). For details on the numerical model and SGS model, the reader is referred to Cintolesi et al. (2015) and to literature therein reported.

In order to simulate high-Reynolds number flows, the first grid point off the wall is placed within the inertial part of the boundary layer and the presence of the wall is accounted for through the use of a wall-layer model. We use an equilibrium wall stress model, in which the wall stress is obtained from instantaneous horizontal velocity at the first off-wall centroid based on law of the wall (details are in Fakhari et al. (2018)).

2.1 Acoustic model

To reconstruct the acoustic field we adopt the advective FWH equation formulated in Cianferra et al. (2018). We briefly recall a scheme of the integral FWH equation:

$$\hat{p}(x,t) = \int [\text{thickness + loading}]_\tau dS(y)$$

$$+ \int [\text{quadrupole}]_\tau dV(y)$$

(3)

The derivation of the advective form of thickness and loading terms in eq. (3) is described in detail in Najafi et al. (2011). The derivation of the advective form of quadrupole term in eq. (3) is described in detail in Cianferra et al. (2018,2019).

Here we consider a rotating frame of reference, since the CFD simulation is carried out likewise. Thus, when computing the distance $r = |x(t) - y(\tau)|$ inside the integrals, where $x$ is the measurement point (also referred to as probe or microphone) and $y$ is the source point (which varies along the solid surface or along the volume), one need to consider the measurement point $x$ as it were rotating with angular velocity $\Omega = |\omega|$. All the FWH integrals, sketched in equation (3) are directly evaluated. The term “directly” refers to the fact that, in principle, the source time and the observer time would be different. This difference is commonly addressed as time delay and is embodied, in mathematical terms, by the appearance of the subscript $\tau$ in the integral kernels and $t$ which results as the observer time on the LHS of equation (3). However, whether the observed phenomenon is under certain conditions, this difference $|t - \tau|$ is negligible and the subscript $\tau$ may be ignored. The conditions for which the simplification is allowed are described in Cianferra et al. (2019), for what concerns immobile immersed object, while are addressed in Linnell et al. (2013) regarding rotating propellers.

Following the latter reference, we evaluate the retarded surface $\Sigma$ in order to highlight the fact that the difference between $t$ and $\tau$ in this case is negligible. The procedure of calculating $\Sigma$ consists of:

- set a time $t^*$ of acoustic signal reception;
- calculate $\tau$ with the bisection method on the function $f(\tau) = t^* - \tau - |x - y(\tau)|/c_0$ where $y(\tau)$ are the points on the propeller that are rotating and $x$ is a microphone location;
- once $\tau^*$ is found that satisfies $f(\tau^*) = 0$, we calculate $y(\tau^*)$ that corresponds to the retarded surface.

The expected result is that the retarded surface practically coincides with the solid propeller surface. This is reasonable at very low rotational Mach numbers, as the one considered in this study. It means that no overlapping of pressure signals, over the sampled time windows, is occurring, and that direct integration of kernels is allowed. This become significant when the volume integrals are considered (see [3] for a discussion).

3 ISOLATED MARINE PROPELLER

In this study we refer to a benchmark propeller, the SVA VP1304, designed for the smp workshops, in order to collect reliable experimental data. All the documentation, including the geometry, experimental data, numerical results from simulations, is available at https://www.svapotsdam.de/en/potsdam-propeller-test-case-ppc, for both the uniform and non-uniform flow cases. The benchmark was introduced and discussed in the International Symposiums on Marine Propulsors of 2011 and 2015 respectively.

In the present study, we carry out the analysis of the propeller for a single value of the advance ratio

$$J_v = \frac{U_a}{nD} = 1.0683,$$

(1)
where \( U_a \) is the velocity along the direction of motion, \( n \) is the rotational velocity in revolutions per second (rps) and \( D = 0.25 \text{ m} \) is the diameter of the propeller.

For the value of \( J_v \) herein considered, the values of the thrust (\( K_T \)) and torque (\( K_Q \)) coefficients are respectively:

\[
K_T = \frac{S}{\mu n^2 D^4} = 0.3538, \quad K_Q = \frac{Q}{\mu n^2 D^5} = 0.09096,
\]

where \( S \) and \( Q \) are the thrust and the torque provided by the propeller. In the experimental set-up the rotation direction is right-handed.

The cylindrical numerical domain used for the LES is sketched in Fig. 1; it has a diameter of \( 7D \), and length of \( 10D \) as suggested in Kumar & Mahesh (2017). The blades plane is located \( 3D \) downstream the inlet and \( 7D \) upstream the outlet section. The grid is obtained in the following way: a cylindrical O-grid is created with streamwise cell clustering increasing close to the hub and the blades region, and with grid coarsening moving towards the lateral boundaries; the OpenFoam tool SnappyHexMesh is adopted to correctly reproduce the geometry. The mesh quality parameters fit the OpenFoam criteria. The total number of cells is around 4 millions for a preliminary mesh, and about 6 millions for the final mesh in which the wake region is refined in order to reproduce adequately the tip-vortex as well as the wake features. At the blades, both meshes have an uniform value of the first drid point off-the-wall \( y^+_1 \sim 13.6 \), achieved without the need of using prismatic layers (\( y^+_i = y_i/(\nu/u_\tau) \) where \( u_\tau = \sqrt{\tau_w/\rho_0} \) with \( \tau_w \) the mean shear stress).

![Figure 1: Computational domain used for the Large Eddy Simulation.](image)

A uniform flow field with mean velocity \( U_a = 4 \text{ m/s} \) is imposed at the inlet, slip condition is given at lateral boundaries and zero gradient condition is enforced at the outlet. At the solid walls of the shaft, hub and blades, the tangential velocity is imposed based on \( u_t(r) = \Omega \times r \), with \( r \) distance from the rotation axis, and \( \Omega = 2 \pi n \), with \( n = 15 \text{ rps} \). The LES is started from a solution obtained with a RANS model in order to avoid the initial transitional development phase.

3.1 Fluid-dynamic analysis

The simulation results are compared with the experimental data. The numerically computed force and torque over the five blades give coefficients:

\[
K_{Ts} = 0.3650, \quad K_{Qs} = 0.09277 \quad (2)
\]

corresponding to errors of

\[
e_{K_T} = 3.18\%, \quad e_{K_Q} = 1.89\% \quad (3)
\]

The signal in time of the \( K_T \) is shown in figure 2, over the period of time between 50 and 200 degrees of rotation. Also, the figure reports the value of \( K_T \) averaged in time.

![Figure 2: Time record of the \( K_T \) coefficient and mean value (straight line) obtained in the simulation.](image)

In figure 3 the coherent structures associated to both the tip and the shaft vortex are made visible through the Q criterion. The isosurface given by \( Q = 10000 \) is contoured by vorticity magnitude (top panel) and Lighthill term (bottom panel). By Lighthill term we mean the scalar \( \partial^2 T_{ij}/\partial x_i \partial x_j \), which is the instantaneous field that acts as quadrupole source in the differential FWH equation. The Lighthill term is found to assume higher values along the shaft vortex, with respect to the tip vortex. It is also relevant, as already reported in experimental works and previous numerical studies, how the shaft vortex persists longer, along the propeller wake, with respect to the tip vortex, which begins to dissipate at about 3 propeller diameters. In the next section, the energetic and long wavelength shaft vortex is investigated as a considerable source of noise.
3.2 Acoustic analysis

The control domain $V$ was chosen as depicted in figure 4, namely a cylinder of radius $1.2R$ that refer to as control domain A. The surface integrals were performed along the patches blade, hub and shaft.

We report the acoustic measurements, evaluated through the FWH equation, relative to four microphones M1,...,M4, listed in Table 1. Two probes, M1 and M2, are located on the propeller plane $x = 0$, at distance respectively of $1.5R$ and $3R$ from the axis of rotation. A third microphone M3 is located at distance $1.5R$ from the axis of rotation and moved downstream, at $x = 3R$. A fourth microphone M4 is on the wake, along the axis of rotation $y = z = 0$, at $x = 20R$. The comparison of the FWH pressure signature is in figure 5. We report the Sound Spectrum Level evaluated as $SPL = 20 \log_{10}(A/p_{ref})$, being $A$ the amplitude of the signal and $p_{ref} = 1\mu Pa$ the reference pressure for underwater measurements. The signal is strongly periodic with a frequency equal to 15 Hz, which is the revolution frequency $n = 15$ rps. The first microphone M1, close to the propeller, shows a second high peak on the blade frequency $nN = 75$ Hz, being $N$ the number of blades. Also, it is apparent that the first harmonic, at 30 Hz, is an observable peak, contrary to the frequency twice the revolution frequency, at 30 Hz, which is barely noticeable. However, the peak in correspondence of the blade frequency is still detectable, and it reaches about 110 dB. The microphone moved downstream, located above the wake M3, shows that the higher frequencies tend to disappear, contrary to the low frequency signal which still get to about 130 dB. This frequency, also called hub frequency, is due to the vortex present around the shaft, persistent in the downstream region and characterized by high vorticity. Finally, the fourth microphone M4, located behind the propeller wake, shows a clear tonal noise, based on the shaft frequency. Even if the distance of the microphone is about 20 R, the signal has an amplitude of about 110 dB.

Table 1: List of measurement points where the FWH pressure is evaluated.

<table>
<thead>
<tr>
<th>x</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3R</td>
<td>20R</td>
</tr>
<tr>
<td>1.5R</td>
<td>3R</td>
<td>1.5R</td>
<td>0</td>
<td></td>
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<td>0</td>
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</tbody>
</table>

The FWH equation (3) is composed of surface and volume integrals, also referred to as linear and non linear terms. The FWH signals showed in Figure 5 are decomposed in the linear contribution, in Figure 6, and non linear contribution in Figure 7. Results in Figure 6 show how the linear terms detect only the blade frequency, except for the microphone M3 above the wake, where probably the shaft vortex produces low-frequency loads on the shaft surface, giving rise to an observable peak at 15 Hz. However, the peak at 15 Hz reaches an amplitude of about 50 Hz, which is very low compared to the complete FWH signal of Figure 5. It is remarkable the linear signal at microphone M4, which is completely below zero decibels.

In Figure 7 the non linear contributions relative to the four microphones are depicted. They clearly show how the complete pressure signals previously seen in Figure 5 are, for the most part, due to the volume terms of the FWH equation, above all as regards the low frequencies. In particular, the peak at 15 Hz, that is predominant behind the wake (see microphone M4), is given exclusively by the FWH volume terms. A study on the directivity, related to the various components of the FWH equation, can deepen this interesting aspect.

Figure 3: Visualization of the tip-vortex coherent structures through the Q criterion. Isosurface $Q = 10000$, together with contour of vorticity magnitude (top panel) and contour of the Lighthill term (bottom panel).

Figure 4: Sketch of the acoustic control domain adopted for the FWH integration: blue cylinder A of radius $1.2R$. The FWH equation (3) is composed of surface and volume integrals, also referred to as linear and non linear terms. The FWH signals showed in Figure 5 are decomposed in the linear contribution, in Figure 6, and non linear contribution in Figure 7. Results in Figure 6 show how the linear terms detect only the blade frequency, except for the microphone M3 above the wake, where probably the shaft vortex produces low-frequency loads on the shaft surface, giving rise to an observable peak at 15 Hz. However, the peak at 15 Hz reaches an amplitude of about 50 Hz, which is very low compared to the complete FWH signal of Figure 5. It is remarkable the linear signal at microphone M4, which is completely below zero decibels.

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CONCLUSIONS

The present study deals with the hydroacoustic field of an isolated marine propeller. The fluid dynamic field is developed through a Large Eddy Simulation, adopting a wall-model to skip the resolution of the viscous sub-layer and the dynamic Lagrangian model to account for the contribution of the sub-grid scales of motion. The acoustic field is reconstructed with the Ffowcs Williams and Hawkings equation, by integrating on the propeller-shaf-hub surface to obtain thickness and loading noise, and by integrating on a cylindrical region of fluid to account for the quadrupole noise. Results of acoustic pressure spectra, evaluated at four microphones, show high noise peaks at the low frequency \( n = 15 \) Hz (being \( n \) the number of revolutions per seconds), and at the blade frequency \( nN = 75 \) Hz. Together with, in some cases, the super-harmonics of the low frequency. Moreover, the low frequency is found to persist downstream, and to be predominant. Comparing the contribution of the linear vs non-linear terms of the FWH equation, is evident how the low frequencies are due exclusively to the vorticious wake.

REFERENCES


