Farassat's formulations in marine propeller hydroacoustics

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ABSTRACT
The aim of this work is to show the potential of the Acoustic Analogy in the analysis of the underwater noise generated by a marine propeller. In particular, some formulations proposed by Feri Farassat are used to conduct an investigation on an interesting and rather unknown aspect of the problem: the identification of the most significant noise generating mechanisms taking place underwater and related to the propeller. Sample numerical results are presented, that were obtained by coupling an incompressible hydrodynamic code to an acoustic solver based on the Ffowcs Williams-Hawkings (FWH) equation, suitably designed to manage the huge set of data from the hydrodynamic simulation. A surprising outcome is that, contrary to popular belief and regardless of the low blade rotational speed, a reliable hydroacoustic analysis of a marine propeller seems to require the computation of the FWH equation’s nonlinear quadrupole sources and cannot leave apart an accurate estimation of the three-dimensional turbulence and vorticity fields.

1. INTRODUCTION
Shipping noise is raising great concern worldwide. Studies have shown that shipping has caused, over the last three decades, an increase of 20 to 30 dB of the sea natural background noise level, especially in the frequency range 10-300 Hz, which is particularly hazardous for marine life. For this reason, several international associations and national governments urge to reduce noise emission from existing ships and improve the hydroacoustic design of new ones. The International Maritime Organization (IMO) selected this as a high priority item to its Marine Environment Protection Committee (MEPC), and a number of Research Projects are funded to face the problem of ship underwater noise. Besides, new standards concerning the noise measurements at sea for different types of vessels are being released, to provide guidelines and issue more stringent regulations. The increasing demand for an acoustically optimized design of ships has to comply with usual requirements concerning, for example, performance and operational costs, while a validated prediction approach is not yet available. However, literature offers interesting contributions on underwater noise measurements, concerning particular types of ship (see, for example, [1–4]), and pointing out the negative effects of shipping noise on marine mammals [5, 6].

A numerical hydroacoustic characterization of a complete ship, identifying the main noise sources, is still a matter of research, rather than a design practice. This represents a significant deficiency of

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the shipbuilding industry and may be a critical issue in the future. Marine propeller is an important source of noise, especially when experiencing cavitation phenomena. Cavitation causes a dramatic increase of pressure and, in general, a noise signature with a high-frequency content; the dynamics of cavitation, however, depends on operating conditions, and the mechanism of sound radiation due to the appearance, growth and collapse of vapor bubbles in water is not yet clear. Underwater noise is also radiated through the hull vibration, caused by the main engines and gearboxes, the unsteady loads induced by the propeller, the turbulent boundary layer and, in general, the external flow conditions. At the same time, the hydroacoustic pressure field can be affected by wave breaking phenomena (especially at the bow region), sound scattering by the free surface (and sea bed in shallow water) and the mutual interactions among different ship components (propeller and hull or rudder, appendages and so on). A short overview is given in this paper on how noise prediction methods using accurate descriptions of the flow field, and based on original aeroacoustic formulations (mostly developed or, at least, worked out by Feri Farassat) can be used in marine applications.

The form of the Acoustic Analogy mostly proposed for the prediction of noise from moving bodies is based on the solution of the Ffowcs Williams-Hawkings (FWH) equation [7]. In the recent years, this numerical approach is being used increasingly for applications to marine and maritime problems. In [8] a noise prediction was carried out for a non-cavitating propeller with and without a duct, by coupling the so-called Farassat time-domain formulation 1A [9] to a hydrodynamic BEM solver based on a potential approach. Some years later, the same numerical procedure was used to account for the presence of a sheet cavitation [10], although in that work no particular algorithm was implemented to deal with the occurrence of the bubble or to investigate its acoustic radiation, and the high frequency content of noise signals was admittedly removed. The robustness of the Acoustic Analogy and its advantages compared to a direct pressure estimation by the Bernoulli equation were discussed in [11], where the role played by the numerical modeling of the propeller wake is analysed in detail. Some preliminary interesting results of propeller noise prediction in the presence of sheet cavitation were published in [12]. There, starting from the knowledge of the bubble shape time evolution, the linear terms of the FWH equation were evaluated as emitted from a source of variable shape (the blade plus the bubble) and the expected impulsive waveform of the noise signals was obtained, with an overall hydroacoustic behavior very similar to a monopole source with high frequency content. An alternative FWH-based approach to deal with the hydroacoustic effects of a sheet cavitation was introduced in [13] to describe the effects of transient cavitation on the noise of a propeller operating in an inhomogeneous flow, even in the presence of a scattering plate simulating the aftbody of a ship hull. All papers mentioned limit their numerical investigations to a propeller in open water and some physical or numerical aspects of the problem, but avoid to perform a comprehensive hydroacoustic analysis through the Acoustic Analogy. In particular, they always assume that the effects of the FWH equation’s nonlinear terms (the so-called quadrupole noise) can be neglected because of the low rotational speed of the blade.

Within this context, however, an interesting question arises: what is the acoustic efficiency of the linear terms for a blade of a marine propeller? Are we sure their role is dominant for any type of low tip speed rotating blade and that the quadrupole nature of nonlinear sources make them always negligible with respect to the linear terms? The design of marine propellers is characterized by very compact planforms (low aspect ratios), a thick shape and noticeable spanwise distributions of twist, skew and, if any, rake. Besides, installation effects make a significant difference between the two cases. An aeronautical propeller mostly operates in a sort of undisturbed medium, or at least a very smooth flow, while a marine propeller works in the rear part of the hull, with an inflow heavily affected by an intense turbulence giving rise to an irregular distribution of velocity. There, the
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propeller somehow enforces its own blade passage frequency to the turbulence and vorticity fields, moving a huge mass of water and giving rise to a vortical wake, whose structure and breaking phase can strongly depend on the operating conditions. This wake persists both in time and space and its effects on the hydroacoustic far field have never been numerically investigated. In other words, by even assuming the absence of any cavitation phenomena, to neglect the only integral terms in the FWH equation accounting for the possible field noise sources is a simplifying assumption to be carefully checked. As a matter of fact, it will be shown in the following how the thickness and loading noise generated by a marine propeller give an unexpectedly small contribution to the pressure field far from the body, where the nonlinear sources are still effective. The simulations will be performed by coupling a full unsteady, three-dimensional incompressible solver to a hydroacoustic code implementing alternative solution forms of the FWH equation. Most of the calculations shown here refer to scaled models, for which experimental data, coming from towing tank and/or circulating water channel tests, are available. However, these tests only concern the hydrodynamic aspects of the problem, since the sound refractions at the wall boundaries of the facility make any noise measurement hardly suitable to validate predictions. For this reason, the available experimental data on scaled models will be only used to validate the hydrodynamic simulations, while the corresponding noise predictions based on the FWH equation will be compared with the pressure signatures provided by the same hydrodynamic code.

The structure of this paper is as follows. Section 2 briefly summarizes the background of theoretical and computational hydrodynamics models to deal with this challenging problem. The high performance and reliability achieved by Computational Fluid Dynamics (CFD) in the context of naval design and analysis enable an exhaustive prediction of a number of complex hydrodynamics problems, concerning both the global “ship-system” and many of its sub-components. Such a level is absolutely not comparable to the present capability of hydroacoustic simulations, even though the acoustic pressure field is intimately related to hydrodynamics. In section 3 it is shown how effective numerical procedures — conceived, developed and validated for aeroacoustic problems in the last three decades — have been increasingly adopted in recent years for the prediction of noise generated by marine propeller and the whole ship, leading to significant progress in this field. Section 4 is devoted to the presentation and assessment of some interesting numerical results, based on both RANS and DES hydrodynamic simulations.

2. PROPELLER HYDRODYNAMICS MODELS

The prediction of noise can be achieved by a direct approach and/or a hybrid method. In the first case the noise is determined together with the flow field, and the numerical scheme is adopted to properly achieve the required assessment of the different flow scales. In principle, a direct numerical simulation (DNS) resolving all flow scales would provide the most complete picture, but the currently available computational resources do not allow to perform such a simulation, especially at the Reynolds numbers of full-scale ships. Then, a feasible alternative is a large-eddy simulation (LES), where a filtering process is applied so that only the dynamically important flow scales are resolved and the smallest ones are modeled, or a Reynolds averaged Navier-Stokes method (RANS), where only the largest flow structures are taken into account through an averaging procedure, or even a suitable combination of the different approaches, as the detached-eddy simulation (DES).

The alternative methodology to the prediction of noise is the hybrid approach, also referred to as transport technique. In this case, the schemes described above for the hydrodynamic analysis are used to obtain a representation of the sources in terms of the physical quantities responsible for
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the production of sound, while different techniques, mostly based on integral formulations, are used to simulate the propagation of disturbances and sound field thereby generated. This is the method adopted here, based on different versions of tools that, as we will see in the next section, could be generally called Acoustic Analogy.

For the description of sound sources used in the application of the Acoustic Analogy proposed in this paper, we use a three-dimensional, unsteady and incompressible hydrodynamic code, which implements both a Reynolds averaged Navier-Stokes (RANS) and a Detached Eddy Simulation (DES) approach. The main difference between these alternative techniques stands in their capability to provide a detailed description of the vorticity and turbulent fields occurring in the flow region downstream the propeller. In a standard RANS code the turbulent viscosity is convected in the flow by a transport equation and does not depend on the size of the computational cell: the procedure averages the value of the velocity everywhere in the field, and the modeling of its turbulent component (here carried out by the Spalart and Allmaras one-equation model [14]) always gives rise to a significant diffusion of the numerical solution. Thus, the vorticity is soon smeared out in the downstream region. In a DES code the RANS solution is strictly applied in the proximity of the body and the eddy viscosity depends on the mesh spatial resolution and the distance from the rigid surfaces: the more the computational cell is small, the more it reduces moving far from the body. This means that by using a rather fine mesh, the blade detached eddies are determined in a sort of direct way and the undesirable numerical damping effects of RANS are notably reduced.

As usual, the problem has to be closed by enforcing appropriate conditions at physical and computational boundaries. On solid walls, velocity is set to zero (whereas no condition on the pressure is required); at the (fictitious) inflow boundary, velocity is set to the undisturbed flow value, and the pressure is extrapolated from inside; on the contrary, the pressure is set to zero at the outflow, whereas velocity is extrapolated from inner points. Let us note that initial conditions have to be specified for the velocity field. In our code, a fully coupled implicit finite volume formulation is implemented. The dual time stepping approach (see e.g. Merkle [15], that generalizes the pseudocompressibility method [16] to unsteady problems) is used and the numerical solution of the discretized form of RANS equations is computed as the asymptotic solution of an auxiliary unsteady problem in a pseudo-time. This system of equations (that includes an evolution equation for the pressure) is hyperbolic in the pseudo-time for its eulerian part; therefore, numerical methods developed for compressible flow simulation can be adopted.

A very good agreement is observed between both the RANS and DES hydrodynamic simulations and some available measurements in [17], in particular concerning the performance characteristics of the propeller (thrust, torque and efficiency curves), which provides confidence in the accuracy of the computed blade hydrodynamic load. It is worth mentioning that significant improvements have been observed recently in the acoustic results based on the representation of turbulent flow fields obtained by a Large Eddy Simulation (LES). Further experience is certainly required before this can be considered a standard methodology to feed acoustic tools for the application in underwater noise problems, but a large joint effort from the CFD and acoustics research communities has been spent over the last decade, leading to promising results that seem to confirm the potential of these combined techniques [18].

3. PROPELLER HYDROACOUSTICS MODELS

The form of the Acoustic Analogy mostly proposed for the prediction of noise from moving bodies is based on the solution of the FWH equation [7]. This is a rearrangement of the basic conservation laws
of mass and momentum into an inhomogeneous wave equation, where the different noise generation mechanisms are identified and expressed by separate source terms. Using the free-space Green’s function for the wave equation allows to write the two linear terms in the following integral form

$$4\pi p_L(x, t) = \frac{\partial}{\partial t} \int_S \left[ \frac{\rho_0 v_n}{r|1 - M_r|} \right] \tau dS + \frac{1}{c_0} \frac{\partial}{\partial t} \int_S \left[ \tilde{p} \hat{n} \cdot \hat{r} \right] \tau dS + \int_S \left[ \tilde{p} \hat{N} \cdot \hat{r} \right] \tau dS. \quad (1)$$

Here $\tilde{p}$ is the pressure distribution on the body surface $S$, $r$ the source-observer distance, $\hat{n}$, $\hat{r}$ the unit vectors along the outward normal to $S$ and the radiation directions, respectively, $v_n$ is projection of the body velocity along $\hat{n}$ and $M_r$ the projection of the local Mach vector along $\hat{r}$. Note that all the integral kernels are evaluated at the emission (retarded) time $\tau$ which represents, for any observer time $t$ and location $x$, the instant when the contribution to the noise signature was released. The difference between $t$ and $\tau$ is known as the compressibility delay and represents a fundamental feature of the acoustic integrals: it follows from the fact that sound propagates in the flow field at a finite speed. Eqn. (1) is known as Farassat formulation 1 [19] and is generally solved by taking the time derivatives inside the integral sign, thus obtaining the standard formula for the aeroacoustic analysis of rotating blades (the aforementioned formulation 1A). The complete derivation of Formulations 1 and 1A is given in [20].

Concerning the nonlinear volume term of the FWH equation, the same use of the free-space Green function turns it into the following form

$$4\pi p_{NL}(x, t) = \frac{1}{c_0^2} \frac{\partial^2}{\partial t^2} \int_V \left[ \frac{T_{rr}}{r|1 - M_r|} \right] \tau dV + \frac{1}{c_0} \frac{\partial}{\partial t} \int_V \left[ \frac{3T_{rr} - T_{ii}}{r^2|1 - M_r|} \right] \tau dV + \int_V \left[ \frac{3T_{rr} - T_{ii}}{r^2|1 - M_r|} \right] \tau dV. \quad (2)$$

The integration domain $V$ represents the three dimensional space outside the body surface $S$, where the presence of the moving body affects the state of the medium. The acoustic effects of the viscous terms are generally neglected and the compressive stress tensor is reduced to the scalar pressure field on the body surface: $\Delta P_{ij} = (p - p_0)\delta_{ij} = \tilde{p}\delta_{ij}$. So, the Lighthill stress tensor is

$$T_{ij} = \rho u_i u_j + (\tilde{p} - c_0^2 \tilde{\rho})\delta_{ij}, \quad (3)$$

and it’s worth noting that the term in brackets represents the nonlinear gap in a series expansion of the pressure-density relationship by accounting for an isentropic transformation (for which the linear term just reads: $\tilde{p} = c_0^2 \tilde{\rho}$, $\tilde{p}$ being the acoustic pressure disturbance).

The implementation of formulation 1A is rather straightforward and can be realized by both a forward- and a backward-in-time integration scheme. In the first case the observer time $t$ is assumed to be unknown and by moving forward in time (starting from a prescribed emission time $\tau$) the resulting noise signature is obtained through an interpolation of the different, time-shifted sources’ contributions. Alternatively, by fixing the instant $t$, it is possible to go backward in time to compute the corresponding $\tau$ and the retarded integral kernels. In this case, when a rotational motion occurs, an iterative procedure must be used. In general, a simple zeroth-order formulation is sufficient to achieve an accurate and effective noise prediction, according to the accuracy and reliability of the
aero/hydrodynamic surface loads. The evaluation of the quadrupole volume integrals, on the contrary, requires the knowledge of the flow field velocity, pressure and density, and a three-dimensional integration.

Eqns. (1) and (2) represent a direct integral solution of the FWH equation. There exists, however, an alternative solving formula. By moving the integration domain on a surface \( S_p \) placed far from the body, the FWH equation remains valid but the impermeability condition \( u_n = v_n \) has no longer to be applied. Thus, \( S_p \) plays the role of a porous (or permeable) manifold, where the velocity field \( u \) (appearing in the corresponding integral kernels) is affected by the nonlinear sources in the flow between the surfaces \( S \) and \( S_p \). For this reason, the use of \( S_p \) as a radiating domain in the FWH equation will account for the nonlinear effects on the pressure far field. If this control surface is placed in order to include all the sound sources, the contribution from the volume integrals tends to zero and an overall noise prediction is carried out through the computation of surface integrals only.

The porous formulation was treated by Ffowcs Williams and Hawkings in their original paper, but it was di Francescantonio [21] who, combining their idea with Farassat’s work on Kirchhoff formulation [22, 23], proposed the porous surface approach as a possible numerical solution of the FWH equation, by assuming

\[
U_i = \left(1 - \frac{\rho}{\rho_0}\right) v_i + \frac{\rho}{\rho_0} u_i, \quad L_i = P_{ij} \hat{n}_j + \tilde{\rho} u_i (u_n - v_n). \tag{4}
\]

In this manner eqn. (1) is formally not altered and gives rise to the following formula

\[
4\pi p(x, t) = \frac{\partial}{\partial t} \int_{S_p} \left[ \frac{\rho_0 U_n}{r |1 - M_r|} \right] \tau \, dS_p
+ \frac{1}{c_0} \frac{\partial}{\partial t} \int_{S_p} \left[ \frac{L}{r |1 - M_r|} \right] \tau \, dS_p + \int_{S_p} \left[ \frac{L}{r^2 |1 - M_r|} \right] \tau \, dS_p + \hat{p}_Q(x, t). \tag{5}
\]

The term \( \hat{p}_Q(x, t) \) still indicates the noise contribution of the field quadrupole sources in the region here outside \( S_p \), which (if the closed surface \( S_p \) includes all meaningful nonlinear terms) should be negligible. Note that by moving \( S_p \) into the flow field, the surface source terms lose their physical meaning of thickness and loading noise related to the fluid displacement and airload distribution caused by body shape and motion. From a practical point of view, however, the porous formulation is certainly the most suitable and effective way to solve the FWH equation. The difficulty lies in obtaining accurate input data on a surface far from the body-source and may require a high level computational capability in solving the corresponding hydrodynamic or aerodynamic problem. In other words, eqn. (5) makes the noise prediction a pure post-processing of the aero/hydrodynamic data.

4. SAMPLE RESULTS FROM NUMERICAL SIMULATIONS

A numerical investigation on the sound field of a scaled model of a conventional marine propeller in a uniform flow at different (noncavitating) operating conditions is presented here. The scaled model allows to limit the Reynolds number of the hydrodynamic simulation and to compare the numerical results with experimental data carried out in standard towing tank tests. The test is performed on the INSEAN E779A four-bladed propeller shown in Figure 1, while the main geometrical and operational parameters of the propeller are reported in Table 1. The test refers to an advance ratio \( J = 0.71 \). It is worth noting that, due to the steadiness of the hydrodynamic problem, the RANS
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solver can be used in a steady operational mode by fixing a suitable convergence condition. On the contrary, the DES solution (although stored at some “regime” condition concerning one revolution period) always requires a full-unsteady simulation in order to provide a reliable description of the vorticity field and the possible flow instabilities occurring in the downstream flow.

Figure 1: Rear and side views of the INSEAN E779A scaled propeller model.

Table 1: Propeller parameters.

<table>
<thead>
<tr>
<th>INSEAN E779A model</th>
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<tr>
<td>Number of blades</td>
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<tr>
<td>Diameter</td>
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<tr>
<td>Expanded area ratio</td>
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<td>Pitch ratio (at 0.7R)</td>
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<td>Hub ratio</td>
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<td>Turning rate</td>
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A qualitative comparison between the alternative hydrodynamic simulations is shown in figure 2, by an effective representation of the vortex released at blades’ tips and spreading downstream (see [24] for details). Note that the computational mesh for the two runs is exactly the same, as well as the range of the quantity used to represent the vorticity, so that the only difference stands in the way we account for the turbulent component of the velocity. The RANS wake exhibits three subsequent spirals before damping down, up to completely disappear, while the DES simulation points out the persistence of a very regular vortex along the whole computational domain. Furthermore, the RANS model does not show any swirling wake from the propeller hub, which, on the contrary, is revealed by the alternative DES solution.

Figure 2: Comparison between the RANS and DES solutions.

The hydroacoustic analysis is carried out through a direct estimation of the only linear terms (Farassat formulation 1A) and an overall noise prediction (porous formulation), thus accounting for the contribution of the quadrupole nonlinear sources. In this case, a closed cylindrical surface, embedding the propeller and the whole flow region theoretically affected by its motion, is adopted as the integration domain. Note that this surface is a part of the hydrodynamic mesh and this allows to avoid any data-fitting procedure on the hydrodynamic data. All the measurement points are located in the proximity of the body. In this way, in spite of the incompressibility assumption characterizing both the RANS and DES simulations and the consequent denial of any propagation phenomena, the noise prediction can be reasonably compared with the pressure provided by the hydrodynamic solutions (see [17]).

Four hydrophones, depicted in Figure 3, are aligned along the direction of propeller axis: points A1 and A2 are located in the disk plane, while points B1 and B2 at more critical downstream locations;
the same figure reminds the boundaries of the downstream tip vortex as computed by the RANS and DES simulations. The right picture depicts the cylindrical surface used as the porous integration domain of equation (5).

Each picture in figure 4 shows the DES/RANS pressure and the noise prediction at the aforementioned points in one revolution period by the formulation 1A, thus accounting for the thickness and loading terms only. At the disk plane point A1 (top-left), very close to the blade tip, the pressure time histories determined through the alternative hydrodynamic approaches exhibit a perfect agreement and the (linear) noise prediction slightly underestimates the pressure peaks. As expected, the noise is dominated by tonal component: the resulting waveform is characterized by the blade passage frequency (BPF) and the possible contribution from nonlinear sources seems to be actually negligible. It is worth noting that the good agreement between these results somehow confirms the substantial equality of the RANS/DES approaches in computing the blade hydrodynamic loads and the practical congruity in comparing the FWH noise predictions with the incompressible pressure time histories in the proximity of the body. As far as we move far from the body, the situation changes. At point A2 (top-right), located in the disk plane, the DES pressure shows some fluctuations and a slightly more irregular waveform, while the agreement between the RANS and the FWH solutions is, in practice, unaltered. It is interesting to note the remarkable reduction of the pressure level: moving from A1 to A2, the peak pressure varies from approximately $\pm 300$ Pa to $\pm 20$ Pa, in spite of the limited distance between the two measurement points. The most interesting results, however, are observed downstream the propeller. At points B1 and B2 (bottom pictures) the RANS solution proves to be unable to provide any (expected) pressure fluctuation in the flow, while the noise contribution from the FWH linear terms is surprisingly close to zero. This means that the decay law of the FWH thickness and loading noise components for a marine propeller is very different from any analogous aeronautical configuration (propellers and/or helicopter rotors) and much steeper compared to the theoretical behavior of a monopole or dipole source. Contrary to the RANS solution, the DES simulation provides a pressure time history no longer characterized by the BPF, but appearing as the most reasonable and reliable result. On the other hand, points B1 and B2 are located in a flow region where the numerical dissipation has gained the upper hand on the RANS solution, while the blade tip vortex spreading downstream is still well depicted by the DES simulation (see right figure 2). This result suggests that “far” from the body the vorticity field plays the dominant role as a (nonlinear) noise source.
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The noise contribution due to the nonlinear sources can be assessed through the porous formulation, by using the cylindrical surface depicted in the right figure 3 as a radiating domain. The results are reported in figure 5, where, for clarity, the computed noise is compared to the DES pressure only. At a first glance, and except for the point A1 (where, as already said, the noise is dominated by the tonal components and the FWH solution now exhibits a slight overestimation of the DES pressure peaks), the FWH porous formulation seems to carry out no reliable solution: the resulting signature at point A2, in fact, shows an appreciable similarity with the DES result, but as we move downstream the propeller the noise predictions are completely different from the hydrodynamic pressure, both in terms of amplitude and overall waveform. Nevertheless, this behavior has a relevant and clarifying explanation. Theoretically speaking, the use of the porous formulation requires a closed integration domain, including all the possible flow noise sources occurring in the flow; then, the porous domain is here composed by a cylindrical lateral surface embedding the blade tip vortex and two “caps”, located upstream and downstream the propeller, according to the boundaries of the computational mesh. From a practical point of view, however, the downstream cap of our porous domain inevitably cuts the tip vortex carried out by the DES simulation, so that if the vortex were a significant source of noise the signatures in figure 5 would correspond to some not-converged solutions.

In order to check the real nature of the signals reported in figure 5, three new hydrophones located halfway the points used in the previous test have been selected and the contributions from the different parts of the porous domain were computed (see figure 6). The results are shown in figure 7. At points C1 (top), still located in the disk plane and very close to the blade tip, the contributions from the two caps are negligible, although the very slight overestimation of the noise corresponding
Figure 5: DES pressure and FWH noise predictions carried out by the porous formulation at hydrophones of figure 3.

to the complete (closed) porous domain already seems to be caused by the downstream cap. Within this context, the limited fluctuations occurring at disk plane point B1 (figure 4) could be reasonably ascribable to the vorticity field too. As we move downstream, the contribution provided by the cap located behind the propeller becomes dominant and heavily affects the overall signature coming from the closed porous domain; on the contrary, the cap immersed in the smooth, uniform inflow ahead the propeller maintains his inert behavior. At point C2 (center), the agreement between the DES solution and the signature provided by only the cylindrical lateral surface is excellent: in practice, the pressure fluctuations occurring in the field and carried out by the hydrodynamic solver just match the contribution of the nonlinear sources distributed along the downstream flow region and corresponding to the spatially persisting vortex released at blade tip. Such an agreement maintains, at least from a qualitative point of view, up to point C3 (bottom), although there it slightly deteriorates because of the proximity of the boundaries of the computational domain.

These numerical investigations on the hydroacoustic behavior of a marine propeller clearly suggest that: i) unlike the analogous aeronautical configurations (and, more in general, a rather common popular belief), the contribution from the FWH linear components rapidly decays moving far from the body and the nonlinear noise sources soon assume the dominant role as generating noise mechanism taking place in the flow, regardless the low rotational speed of the blade; ii) in absence of any cavitation phenomena, the vortex generated at blade tip and spreading in the downstream region seems to be the fundamental source of noise related to the propeller and occurring underwater, with
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a main directivity orthogonal to the axis along which it develops; iii) except for the tonal component and a very limited region in the proximity of the propeller, a RANS simulation appears to be completely inadequate for acoustic purposes.

Figure 6: The different parts of the porous domain and the measurement points used to check the corresponding contributions to the noise signature.

5. CONCLUDING REMARKS AND PERSPECTIVES

The numerical investigations carried out in this paper suggest some interesting and rather new results concerning the hydroacoustic analysis of a marine propeller in a uniform flow. Unlike the well-known and analogous aeronautical case, the contribution from the linear terms of the FWH equation seems to be circumscribed to a spatially very limited region: moving far from the body, the pressure fluctuation rapidly reduces and appears to be substantially related to nonlinear sources (the vorticity and turbulence fields), regardless of the blade rotational speed. In particular, the most important nonlinear generating noise mechanism is the vortex released at blade tip and spread downstream, exhibiting a main two-dimensional directivity orthogonal to the direction along which the vorticity develops.

It is worth reminding that many nonlinear aspects of the problem (as the flow instabilities related to the unavoidable breaking of the tip vortex far from the body or, above all, the occurrence of any cavitation phenomena) are here completely ignored. These effects can do nothing but increase the contribution from the FWH quadrupole terms, so that the predominance of the nonlinear sources in the far field revealed by our analysis is probably underestimated.

Because of the relevant role played by the vorticity and turbulence in determining the characteristics of the acoustic field, the RANS simulation soon becomes inherently inadequate for hydroacoustic purposes, especially at measurement points where the turbulent fluctuating component of the velocity field becomes relevant. In any case, the results presented in this paper demonstrate that the Acoustic Analogy represents a powerful tool to achieve a deep understanding of the main generating noise mechanisms taking place underwater.

The authors also consider this a kind of a tribute to the scientific and educational work of Feri Farassat. He has contributed greatly to the birth and growth of a generation of researchers who were inclined to take different points of view, interested in using a broader set of cultural tools and able to develop advanced methodologies to solve problems of practical interest.
Figure 7: Noise signatures at points of figure 6, as computed from the different parts of the porous domain.
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