Hydroacoustic characterization of a marine propeller through the acoustic analogy

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ABSTRACT: This paper deals with the use of the Acoustic Analogy for the prediction of the underwater noise generated by a marine propeller. Different configurations are treated in order to demonstrate the potentiality of such a numerical approach and to analyze the role played by the different noise sources. Unlike analogous aeronautical propellers, it will be shown that the evaluation of the nonlinear quadrupole sources is relevant regardless of the blade rotational speed. On the contrary, the linear sources (thickness and loading noise) due to the propeller are predominant just in a very limited region, while the only appreciable linear contribution affecting the acoustic pressure far field comes from hull scattering effects.

1 INTRODUCTION

Within the last years the marine scientific community has been paying an increasing attention to many hydroacoustic phenomena concerning the maritime transport and many marine problems. This is due not only to the well-known health and comfort problems onboard or to the operational ability of different ships affected by a high noise level (offshore survey vessels, fishery and ocean research vessels, seismic vessels and others), but also to the environmental pollution of the sea and the negative impact on marine mammals. For this reason, many international organizations are moving towards more and more stringent regulations on underwater noise and some more restrictive certification tests for many types of ships. As a matter of fact, such a general tendency is not related to a satisfactory knowledge of the generating and propagating noise mechanisms in water and looking at the available literature it is easy to recognize a deep lack of both theoretical and, above all, numerical models. At present, the criteria adopted to satisfy the noise emission requirements for a ship are based on empirical basis and the use of some approximated numerical procedure able to provide, to the utmost, a qualitative raw estimation of the acoustic far field.

Among the many sources of sound related to a ship, the propeller plays a primary role. Even at a simple nocavitating condition and at cruising speed, the propulsor acts not only as a direct noise source (being a body moving in the fluid), but also as a sort of indirect source, since it excites the stern vault of the hull by an unsteady (periodic) hydrodynamic load. Thus, the hull itself scatters the pressure and affects the resulting ship underwater noise field. Unfortunately, many aspects of the acoustic behavior of a marine propeller are still completely unknown, as, for instance, the influence of a full-unsteady inflow (as in a manouvering ship), the interactions with hull, rudders and appendages or, above all, the hydroacoustic effects due to the different cavitation phenomena. At present, the selection criteria for a propulsor are strictly limited to the efficiency features (evaluated through the well-known torque and thrust diagrams), while the generated noise is assumed to be a sort of inevitable and unverifiable consequence. This way, the present inability in modeling the underwater noise field could become a critical aspect for many shipyards in the next future, especially in view of the above mentioned and more stringent certification tests.

This situation is rather surprising. Many theoretical and numerical models, originally developed in Aeroacoustics for different rotary-wing propulsion systems, are presently available to analyse the acoustic behaviour of a propeller. For a long time, these models were developed and validated in a lot of national and international research projects and are now used by industry in many applications of practical interest. These models could be successfully adopted to investigate the hydroacoustic behavior of a marine propeller and, in general, to evaluate the noise generated by the ship-system and many of its subcomponents.

Early studies for a rotating blade started in the thirties, when it was already known that both the blade loading and the body thickness could generate noise by separate mechanisms. Most of the early works focused on aeronautical propellers and in
the fifties the application of the theory of Acoustic Analogy (Lighthill, 1952), formulated for the jet noise phenomena, contributed to the enhancement of theoretical approaches. A fundamental step towards a full understanding of noise generated by bodies moving in a fluid was given by Ffowcs Williams and Hawkings (1969), as an extension of Lighthill work. Exploiting the theory of the generalized functions (see Kanwal, 1983), they derived a governing differential equation for the acoustic pressure which has been established as the theoretical basis for a number of modern and sophisticated prediction tools devoted to the prediction of rotating machinery noise. The FWH equation may be considered as an extension of Lighthill equation to take into account the basic mechanisms of noise generation related to the shape of the body and the loads it experiences along its motion through the fluid. In the seventies the research efforts were devoted to the analytical treatment of the FWH equation: the application of the standard Green function technique (Morse, 1953) and some relevant results concerning the generalized derivatives enabled the derivation of useful integral expressions for the sound pressure field. In particular, F. Farassat proposed a number of different forms of solution in time domain (Farassat, 1975 and 1981) which were successfully implemented for the calculation of the FWH linear source terms for an helicopter rotor. Nowadays, these solving formulations represent a standard approach for many computational tools devoted to the aeroacoustic analysis of complex multibodies configurations, and are widely used even in the industrial context.

Unlike the fruitful research in Aeronautics, only few applications of the FWH equation were proposed in the recent years for a marine propeller. A noise prediction was carried out for a non-cavitating propeller with and without a duct (Seol, 2001), by coupling the well known Farassat time-domain formulation 1A to a hydrodynamic BEM solver based on a potential formulation. Some years later, the same numerical approach was used to account for the presence of sheet cavitation (Seol, 2005), although in that work no particular algorithm was implemented to deal with the occurrence of the bubble or to investigate its own acoustic effects, so that any high frequency content of the noise signals was admittedly removed. The robustness of the acoustic analogy and its advantages with respect to a direct pressure estimation by the Bernoulli equation were discussed later (Testa, 2008), by pointing out the role played by the numerical modeling of the propeller wake. Some preliminary interesting results on a sheet cavitation noise prediction were also published (Salvatore & Ianniello, 2003). There, starting from the knowledge of the bubble shape time evolution, the linear terms of the FWH equation were evaluated on a time-dependent radiating domain (the blade plus the bubble) and the expected impulsive waveform of the noise signals was carried out, with an overall hydroacoustic behaviour very similar to a monopole source with a high frequency content. An alternative FWH-based approach to deal with the hydroacoustic effects of a sheet cavitation was introduced (Salvatore, 2006), discussed (Testa, 2008) and used (Salvatore, 2009) to describe the effects of a transient cavitation occurring on a propeller operating in an inhomogeneous flow, even in presence of a scattering plate simulating the aft-body of a ship hull.

A notable limitation, however, of all the aforementioned papers is that the numerical investigations only concern some physical or numerical aspect of the problem and, above all, avoid to perform a comprehensive characterization of the propeller hydroacoustic behaviour. In particular, they always assume that the effects of the FWH non-linear terms can be neglected because of the low rotational speed of the blade, but such a limiting assumption (rather usual in the aeronautical context) has never been confirmed underwater, either from and experimental and a numerical point of view. The main aim of this paper is to investigate on the actual role played by all the noise sources related to a marine propeller and to prove the potentiality of the Acoustic Analogy in the numerical prediction of the underwater noise.

2 THEORETICAL BACKGROUND

The FWH represents an elegant manipulation of the fundamental conservation laws of mass and momentum which gives rise to the following inhomogeneous wave equation written in terms of generalized functions

\[
\frac{\partial}{\partial t} \bar{p}(x,t) = \frac{\partial}{\partial x_i} \left[ \sigma c_n + \rho (u_n - v_n) \delta(f) \right] - \frac{\partial}{\partial x_i} \left[ \left\{ \left[ \Delta \sigma \delta + \rho (u_n-v_n) \delta(f) \right] \right\} \right] + \frac{\partial^2}{\partial x_i \partial x_j} \left( T_{ij} H(f) \right)
\]

The equation \( f = 0 \) is an implicit equation which describes an arbitrary surface, whose choice heavily affects the physical meaning of the different terms. The fluid and surface velocity components are indicated by \( u \) and \( v \), respectively, while the subscript \( n \) indicates the projection along the outward normal to the surface. The D’Alembert operator is given by
\[
\overline{\mathbf{\nabla}}^2 = \frac{1}{c_0^2} \frac{\partial}{\partial t} - \nabla^2
\]

while \( T_{ij} = \rho \frac{\partial u_i}{\partial t} + \rho' \frac{\partial}{\partial t} \delta_{ij} \) is the Lighthill stress tensor, \( \rho' = (\rho - \rho_0) \) the density perturbation, \( c_0 \) and \( \rho_0 \) the speed of sound and the fluid density, respectively, in the undisturbed medium, \( P_{ij} \) the compressive stress tensor \((\Delta P_{ij} = P_{ij} - p_0 \delta_{ij})\) and \( \delta_{ij} \) the Kronecker symbol. The presence of the Dirac and Heaviside functions points out the different nature of the source terms: two surface terms directly related to the effects of the discontinuity \( f = 0 \) in the flow field and a volume term accounting for all noise sources acting outside it. When \( f = 0 \) coincides with the body surface \( S \), the impermeability condition \( u_n = v_n \) simplifies equation (1) and the use of the Green's function approach leads to the following integral equation for the acoustic pressure (at point \( x \) and time \( t \))

\[
4\pi p(x,t) = \frac{\partial}{\partial t} \int_S \left[ \frac{\rho_0 v_n}{r [1 - M_f]} \right] \frac{dS}{r} + \frac{1}{c_0} \frac{\partial}{\partial t} \int_S \left[ \frac{\rho v_n}{r [1 - M_f]} \right] \frac{dS}{r} + \frac{\partial}{\partial t} \int_S \left[ \frac{\rho v_n}{r^3 [1 - M_f]} \right] \frac{dS}{r} + \int_S \left[ \frac{\rho v_n}{r^3 [1 - M_f]} \right] \frac{dS}{r}
\]

This equation is written under the assumption of inviscid flow (thus reducing the compressive stress tensor to the scalar pressure field on the blade surface: \( \Delta P_{ij} = (p - p_0) \delta_{ij} \)) and isentropic transformations, for which the pressure-density relationship can be approximated by the linear term of its series expansion (i.e. \( p' = c_0^2 \rho \)) where \( p' \) denotes the acoustic pressure disturbance). In equation (2) the subscript \( r \) denotes the projection along the source-observer direction, \( M \) is the Mach number and \( r \) indicates the source-observer distance. The surface integrals represents the linear terms and are usually known as thickness and loading noise. The last term \( p_0(x,t) \) represents the so-called quadrupole noise and corresponds to three volume integrals theoretically extended to the whole region flow \( (V) \) affected by the body motion

\[
p_0(x,t) = \frac{1}{c_0^2} \frac{\partial^2}{\partial t^2} \int_V \left[ \frac{T_{rr}}{r [1 - M_r]} \right] \frac{dV}{r} + \frac{1}{c_0} \frac{\partial}{\partial t} \int_V \left[ \frac{3T_{rr} - T_{rr}}{r^3 [1 - M_r]} \right] \frac{dV}{r} + \int_V \left[ \frac{3T_{rr} - T_{rr}}{r^3 [1 - M_r]} \right] \frac{dV}{r} \]

Note that all the integral kernels are determined 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 \( \tau \) and \( t \) is an essential feature of the acoustic integrals and emphasizes that sound propagates at finite speed. By avoiding the computation of the nonlinear quadrupole sources and moving the time derivatives within the integrals, equation (2) gives rise to the formulation 1A (Farassat, 1981), the standard retarded time formula for the linear acoustic analysis of rotating blades. This formula is rather straightforward to be implemented and reduces the noise prediction to a simple post-processing of the aero/hydrodynamic data. On the contrary, the computation of the quadrupole noise is not so easy, and requires the knowledge of the three-dimensional velocity, pressure and density fields, besides to a volume integration. It’s worth noting that when the projection of the Mach vector along the source-observer direction tends to 1, all the integrals become singular. This is an interesting feature of these integral solution forms of the FWH equation which is related, from a physical point of view, to the occurrence of multiple emission times for noise sources moving at supersonic speed (Ianniello, 2007).

Since the last nineties, an alternative integral formulation was proposed to achieve a comprehensive (linear plus nonlinear) evaluation of the acoustic pressure and, at the same time, to avoid any direct volume integration. Such an alternative and effective approach is known as porous formulation. It consists of integrating equation (1) on a closed surface \( S_p \) placed far from the body, which contains all the possible nonlinear sources and where the usual impermeability condition has not to be applied. Although such a method had already been treated by Ffowcs Williams and Hawkings, it was first implemented by Di Francescantonio (1997), by assuming

\[
U_i = \left(1 - \frac{\rho}{\rho_0} \right) v_i + \frac{\rho}{\rho_0} u_i
\]

\[
L_i = \rho_0 \frac{\partial}{\partial t} (u_i - v_i)
\]

In this way, equation (2) is formally not altered and gives rise to the alternative integral solving formula

\[
4\pi p(x,t) = \frac{\partial}{\partial t} \int_S \left[ \frac{\rho U_n}{r [1 - M_f]} \right] \frac{dS}{r} + \frac{1}{c_0} \frac{\partial}{\partial t} \int_S \left[ \frac{L_n}{r [1 - M_f]} \right] \frac{dS}{r} + \frac{\partial}{\partial t} \int_S \left[ \frac{\rho U_n}{r^3 [1 - M_f]} \right] \frac{dS}{r} + \frac{\partial}{\partial t} \int_S \left[ \frac{L_n}{r^3 [1 - M_f]} \right] \frac{dS}{r} + p_0(x,t)
\]

(4)
Here, the term $p_Q$ still indicates the noise contribution of the field quadrupole sources, but in the region outside the porous surface $S_p$. Thus, if this surface is suitably placed in order to include all the possible noise sources, the volume integrals tend to zero and an overall noise prediction can be carried out by surface integrals only. Of course, the weak-point of such a numerical approach is the availability of an accurate and reliable set of data in the flow field external to the body-source.

In the following section, the numerical solutions of all integral equations (2), (3) and (4) will be presented, in order to show the role played by the different sources due to a marine propeller and to demonstrate the potentiality and effectiveness of the acoustic analogy in performing an underwater noise prediction.

3 NUMERICAL RESULTS

The hydroacoustic characterization of a marine propeller through the FWH equation is here tested by taking into account two different problems. As a first step, a simple, isolated (open water) propulsor in a uniform flow will be treated to show the role played by the FWH source terms and the effectiveness of the porous formulation. Subsequently, a mounted propeller on a complete ship model (hull, rudder and appendages) will be taken into account to achieve a deeper understanding of the predominant generating noise mechanisms taking place in the flow field.

In the following sections we will focus our attention on the hydrodynamic numerical simulations used to carry out the requested data. It is sufficient to know that all the simulations are based on full unsteady, incompressible RANSE approaches and provide the pressure and velocity fields around the body-source, as well as the hydrodynamic loads acting on the rigid surfaces. The same (incompressible) pressure signatures computed through the Navier-Stokes simulations in the far field will be used to compare and, somehow, validate the noise predictions. In this context, it is worth noting that from a theoretical point of view, the incompressibility assumption characterizing the RANSE calculations is simply not compatible with any hydroacoustic analysis, since it removes a priori any propagation phenomena (the speed of sound is infinite). In other words, the RANSE pressure does not correspond to what we usually refer to as noise. On the other hand, the region concerned is spatially very limited, compared to the underwater speed of sound and the distances covered by the pressure disturbances. Therefore, from a practical point of view, the available RANSE pressure signals can be reasonably identified with the acoustic pressure time histories in the proximity of the propeller and will be used to assess our hydroacoustic analysis. This way, a good agreement with the RANSE pressure signal should represent a roundabout validation of the FWH noise prediction, as well as a sort of consistency proof between the two numerical approaches. Moreover, as usual for aeronautical applications, the water will be considered as a homogeneous medium, where the sound propagation speed is constant. Of course, this assumption is quite debatable for the sea water, compared to the air: the presence of not negligible temperature and pressure gradients due to depth, the sea currents, the scattering effects of the free surface, the salinity concentration are all variables which can heavily affect the sound propagation. On the other hand, we are here interested on the sound generation phenomena, more than the propagation aspects of the problem, so that this assumption should not affect the main results of our numerical investigations.

3.1 Isolated propeller

An interesting check on the FWH equation capabilities in the analysis of the acoustic behaviour of a conventional marine propeller may be carried out on a very simple configuration: an isolated (non cavitating) propeller in a uniform flow. As already mentioned, the few papers available in literature on this matter, exploits the rather common conviction of a negligible contribution from the nonlinear source terms, due to the low rotational speed. As well-known, this is a quite usual approximation in Aeroacoustics where the quadrupole terms were proven to be relevant only at a high transonic or supersonic speed. This regime is far from the usual operating conditions of a marine propeller. In that case, however, this assumption has a well defined physical explanation: the predominant noise generation mechanisms for a blade rotating in air are related to its shape and, above all, the pressure distributions acting on its surface. These mechanisms are represented by the two linear surface terms of the FWH equation. At a low rotational speed the nonlinear, three-dimensional effects are limited to the turbulence and vorticity fields generated by the blade rotary motion, which do not provide a significant contribution to the acoustic pressure field. Thus, they are usually neglected. On the contrary, at high rotational speed the flow field surrounding the blade suffers the occurrence of a shock wave, which represents a highly nonlinear phenomenon and an intense source of sound. For this reason, at transonic or supersonic regime, the quadrupole noise assumes a fundamental role.

For a marine propeller the situation is very different. The usual rotational speed of a marine
propulsor is not comparable with the speed of sound in water, and the Mach number itself is never mentioned in a hydroacoustic analysis. This, however, does not mean that the three-dimensional, nonlinear sources can be automatically neglected. For example, it is sufficient to consider a propeller exhibiting bubble or cloud cavitation: when the external pressure around a bubble starts to increase, after a very short time the pressure gradient between the outer and inner pressure decreases and the bubble enters a collapsing stage. This stage creates shock waves and, hence, noise. The phenomenon certainly does not depend on some transonic value of the blade rotational speed but its effects on the hydroacoustic far field may be relevant and depend on both the air bubbles size and the flow field area affected by cavitation. In the FWH equation, the only way to account for such a noise source is through the quadrupole volume terms. Generally speaking, a marine propeller generates a vortical wake, whose structure and breaking phase strongly depend on the operating condition. Due to the different density and viscosity of air and water and unlike the analogous condition in air, the turbulence and vorticity generated by the blade rotational motion persist underwater both in time and space and their effects on the hydroacoustic far field have never been investigated. Moreover, in a real ship configuration the propeller works in the rear part of the hull, with an inflow characterized by an intense turbulence and where the propulsor somehow enforces its own blade passage frequency to the turbulence and vorticity fields, moving a huge mass of water. Within this context and even assuming the absence of any cavitation phenomena, the removal of the only FWH integral terms able to account for the possible field noise sources seem to be a rather rash hypothesis.

In order to clarify the role played by the different FWH source terms, a relatively simple investigation has been performed on an isolated, four-bladed marine propeller, by exploiting the availability of a full set of hydrodynamic data from a RANSE simulation. These data include not only the pressure distribution upon the blade surface, but also the velocity and pressure fields around the propeller, thus allowing a direct estimation of the quadrupole integrals. Figure 1 shows a sketch of the tested configuration. Each blade of the isolated propeller is embedded into a 3D mesh (rigidly attached to the rotating body) used to model the boundary layer and the flow in the proximity of the blade itself. This three-dimensional mesh is here adopted as integration domain for the quadrupole volume integrals. Furthermore, the whole propeller is surrounded by a further, cylindrical grid, whose most exterior layer (reported in the Figure by a grey shaded cylinder) is used as the porous surface to carry out the numerical solution provided by equation (4).

From a practical viewpoint, the test refers to the INSEAN scaled model E1630 (with a diameter of 21cm), rotating at 10rps (rounds per second) and in a uniform flow at a velocity of approximately 1.05m/s, so that the corresponding advance coefficient is $J = 0.5$. Figure 2 shows an isocontour map of the pressure field and points out the location of the two hydrophones used for noise predictions. The first is placed very close to the propeller disk plane, where both the FWH thickness and quadrupole source terms usually exhibit a relevant directivity; the second is ($x$) aligned to the first one, but located downstream to the propulsor.

Next two Figures 3 and 4 report the noise signatures (pressure vs time) computed by the FWH solver within a blade revolution period.
Each Figure includes the RANSE pressure signal (labelled “NS”) and the separate contributions from all the three FWH source terms (top picture), a comparison between the Navier-Stokes pressure and both the overall and linear solutions provided by the acoustic analogy (mid picture) and, finally, the signature provided by the porous formulation (bottom picture). As expected, at hydrophone 1 the thickness and loading noise represent the predominant sources, but the quadrupole noise contribution does not look like a negligible term.

This can be well appreciated in the mid Figure, where the agreement between the FWH signature and the corresponding RANSE pressure becomes excellent just accounting for the nonlinear noise sources too. At the same time, also the porous formulation provides a very good agreement with the RANSE signature, both in amplitude and in
the resulting waveform. Moving downstream the propulsor (at hydrophone 2), the pressure signal coming from the hydrodynamic simulation exhibits a very irregular form, probably due to both the effect of the propeller wake and some fluctuation of numerical nature.

All the frames, however, clearly suggest that a pure linear hydroacoustic analysis is not sufficient to determine the actual pressure values. In fact, both the separate contributions from the linear terms (top picture), as well as the overall signature achieved by adding the quadrupole noise (mid picture), give a notable underestimation of the pressure. This result suggests that the selected 3D mesh for the computation of the quadrupole integrals is too much limited from a spatial point of view and a relevant (here missing) contribution from non linear sources is somehow of numerical nature.

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In the following section, these points will be discussed again (and fully confirmed) by an additional test-case concerning a propeller mounted on a patrol boat scaled model.

3.2 The role of the nonlinear sources

The numerical results reported in the last section points out that the rather usual assumption to neglect the nonlinear source terms concerning the propeller (because of the low rotational speed) should be carefully investigated. Such an analysis would require a Navier-Stokes-based simulation of the flow around the whole ship, a simulation very CPU demanding and rather unusual for marine problems. Furthermore, it is useful to remind that the reliability of such simulations is always limited by the available computing resources.

This problem has been faced at INSEAN by accounting for a full unsteady RANSE simulation of a scaled model of a patrol vessel in a steady course. The model includes all the appendages (struts, fins, shaft, bracket) and a propeller working at the propulsion point of the full scale ship. The model length is \( L_{pp} = 5.33 \) m and moves at a speed \( U = 2.52 \) m/s. Consequently, the Reynolds and the Froude numbers correspond to \( 1.18 \times 10^7 \) and 0.348, respectively. The propeller is a four-bladed, adjustable-pitch, skewed model (INSEAN Model E1630) with the shaft attached to the hull by two brackets arranged in the typical “V” configuration. The diameter of the propeller is \( D = 0.21 \) m and its turning rate is set to \( n = 820 \) rpm, so that (in non-dimensional terms) the nominal advance coefficient is \( J = 0.878 \). Figure 5 shows a 3D sketch of the tested configuration (where the symmetry with respect to the vertical plane is still exploited to limit the computational burden). The hydrophone used to our aims is placed in the vertical symmetry ship plane and rather well aligned with the propellers disk (top Figure 6). As a first step, we limit the calculations to the linear contributions from the propulsors, the rudders and the hull, by still using the formulation 1A. The result is reported in the bottom Figure 6 and exhibits a relevant discrepancy with the corresponding pressure signature directly determined by the RANSE solver (and here labeled as ‘NS’). It’s interesting to note that the rudders contribution is very close to zero and, above all, that the thickness and loading noise contributions generated by the propellers are very limited. Furthermore, the overall linear noise prediction seems
to be dominated by the hull scattering effects, but is not comparable with the pressure signal determined by the RANSE solver.

Compared to the few results available in literature, this result is really unexpected. The four-peaked waveform of the NS pressure signature somehow confirms that the propulsor represents the dominant noise source in the field, but the very limited contribution coming from the corresponding thickness and loading terms casts serious doubts on the opportunity to neglect the nonlinear sources. As a matter of fact, the (here missing) quadrupole noise can be the only responsible of such a large discrepancy between the two numerical solutions. Furthermore, the hull scattering effects appear to be the only appreciable linear contribution to the underwater pressure far field.

The computation of the FWH quadrupole source term requires the adoption of a suitable integration domain $V$ and the estimation of the Lighthill stress tensor in the corresponding integral kernels. As mentioned above, the four-peaked RANSE pressure signatures indicate the predominant role of the propellers as noise source. Therefore, our analysis will be limited to the ship aftbody, by exploiting the availability of different mesh blocks of the RANSE simulation to model the flow region in the neighbourhood of the propulsors.

Figure 7 shows a sketch of this region. Here, it is possible to identify: i) a grid embedding each blade as a glove (actually made of five separate blocks with a very fine spatial resolution and substantially devoted to the analysis of the blade boundary layer); ii) a toroidal grid around the propeller hub; iii) a cylindrical mesh embedding the whole propulsor; vi) a block surrounding the rudder and made of two adjacent patches; v) three contiguous cylindrical blocks, located downstream to the propeller. It’s interesting to note that the first cylindrical block rigidly rotates with the propulsor, while the last three ones are fixed (they translate with the model) and are obviously used to achieve an accurate description of the propeller wake. Concerning the computation of the Lighthill stress tensor, we first assume a purely linear relationship between the pressure and the density, so that

$$T_{ij} \approx \rho u_i u_j$$

where, by now, $u_i$ and $u_j$ represent the velocity components directly provided by the RANSE code. Note that such an approximation is rather common also for aeronautical problems (at least up to the condition for which the blade rotational velocity gives rise to a weak shock wave). Next Figure 8 shows the contribution from the linear terms (due to the propellers, the hull and the rudders, already depicted in the bottom Figure 6), the quadrupole noise determined in the selected region, the overall noise signature and the corresponding NS-based pressure signature. The result is very surprising. The contribution from the nonlinear sources is very close to zero and the relevant underestimation...
of the FWH noise prediction with respect to the RANSE solution does not change at all!

Here the problem is the adopted estimation of the Lighthill stress tensor, which is completely unsuitable in our context. In fact, in a RANSE approach the velocity field is assumed to be the sum of a time-averaged value plus a fluctuating term $u = \bar{u} + u'$, so that the second-order tensor $\rho u_i u_j$ should be expressed in the following Reynolds averaged form

$$\rho u_i u_j = \rho \bar{u}_i \bar{u}_j$$

From a numerical point of view, the second term on the right-hand side of this equation must be somehow modeled to account for the velocity fluctuations occurring in the region of interest. This term was not included in the signatures of Figure 8, where the Lighthill tensor was directly determined by the output quantities of the RANSE solver, corresponding to the averaged values of the velocity components only. In order to determine the above mentioned term, we follow (in both the RANSE solver and, now, the FWH formulation) the turbulent-viscosity hypothesis, introduced by Boussinesq in 1877, which models the averaged contribution of the fluctuating terms in a form similar to the stress tensor for a Newtonian fluid. In general, for an incompressible flow, this hypothesis is expressed in the following form

$$Q_{ij} = \rho T \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) + \frac{2}{3} \rho k \delta_{ij}$$

where the positive scalar coefficient $\nu_T$ is the turbulent (or eddy) viscosity (see, for example, Pope, 2000) and represents a further output variable from the hydrodynamic solver. The RANSE solution already incorporates the term representing the turbulent kinetic energy $k$ in the pressure field. Thus, a suitable representation of the Lighthill stress tensor is given by

$$I_{ij} = \rho \bar{u}_i \bar{u}_j - \rho T \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right)$$

where the velocity gradient can be derived from the knowledge of the velocity field by a simple second-order numerical differentiation. The use of the Lighthill tensor expressed by last equation turns the noise prediction reported in Figure 8 into the one reported in Figure 9. The quadrupole noise signature exhibits the expected waveform, with pressure peak values notably larger than the overall linear terms contribution, and the agreement between the RANSE and the FWH noise prediction becomes excellent.

The last Figure suggests a very important and new result. It demonstrates that, unlike the aeronautical case, the dominant generating noise mechanisms taking place in the flow field are not related to the body shape or the hydrodynamic loads acting on its surface, but rather to the notable fluid velocity gradients (mainly due to the propeller) and then to the vorticity and turbulence fields. For this reason, a reliable ship (or propeller) underwater hydroacoustic analysis cannot leave aside the contribution from the nonlinear sources, regardless of the propeller rotational speed. Such an assertion is
highly supported by both the comparison between the noise predictions reported in Figures 8 and 9, and the negligible role played by the thickness and loading source terms due to the propeller.

4 CONCLUSIONS

Within this paper, we’ve tried to show the prediction capabilities of the acoustic analogy in the analysis of a conventional marine propeller and to endorse its own use for hydroacoustic problems. To this aim, different configurations have been analysed: a) the hydroacoustic behavior of a propulsor in open water condition, b) the overall (linear and nonlinear) analysis of a mounted propeller on a scaled model. The most important and interesting result carried out from these numerical investigations concerns the role of the different noise sources related to the propeller and, in general, the ship. Unlike the analogous aeronautical problem, the pressure far field underwater appears to be heavily affected by the nonlinear noise sources, although the blade rotational speed is very far from a transonic regime. Then, the most important generating noise mechanisms seem not to concern the body shape and the hydrodynamic loads on the blade surface, as the vorticity and turbulence fields generated by the propeller. In other words, a reliable estimation of the underwater pressure field must account for an accurate computation of the velocity gradients taking place in the flow.

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