In this paper the noise hydrodynamically generated by noncavitating marine propellers in non-axial flow condition is investigated. The permeable Ffowcs Williams and Hawkings Equation (FWH-P), solved by a Boundary Element Method (BEM), is used to radiate sound outward a suitable fictitious surface that encloses all the sources of sound related to the propeller and flow-field around it. To this aim, the fluctuating velocity and pressure field distributions required upon the permeable surface are obtained by a Detached Eddy Simulation (DES). For validation purposes, the acoustic signatures evaluated by the combined DES/FWH-P approach are compared with those directly computed by the hydrodynamic solver for observers placed in the near field. 

Keywords: Propeller hydroacoustics, Oblique flow, Acoustic Analogy, Permeable surface technique.

1. Introduction

The prediction of noise generated by bodies moving throughout a fluid domain is of great interest for several engineering applications. In this framework, rotary-wing propulsor systems are largely investigated from a numerical standpoint because a driving factor in the design of modern vehicles (such as airplanes and ships) is the acoustic signature to comply with international standards related to environmental issues, comfort onboard, detectability of war units, etc...

Historically, the main issues of aeroacoustic research have been closely related to aeronautical applications, tipically aimed at reducing the emitted noise. From the beginning, aeroacoustics has gained constantly more and more importance due to an increased consciousness of environmental issues and the strong international competition between airplane/helicopter manufacturers pushing toward the design of quieter vehicles (inside and outside the cabin). Although hydroacoustics, i.e. the science of noise generation and propagation mechanisms through water, is relatively younger than aeroacoustics, the basic understanding of hydrodynamically generated sound has increased significantly by the contamination with the developments achieved in the aeronautical context, thanks to the commonalities existing among fluid-dynamics of marine propellers, helicopter rotors and aeronautical propellers. Indeed, this pushed towards the knowledge of the main sources of marine propellers sound, the awareness of the major physical mechanisms governing sound propagation in water and the use of well-assessed numerical approaches.

Among the many theoretical and numerical models used to predict fluid-dynamically generated noise signatures, the Ffowcs Williams and Hawking Equation (FWHE) represents a well-known and widely used approach [1]. It extends the Lighthill theory for turbulence generated noise, to account...
for the presence of solid moving bodies and identifies different noise generation mechanisms consisting of a combination of linear contributions from body surface source terms and nonlinear quadrupole field source terms within a volume of suited extension around the body. These flowfield sources of noise may be acoustically relevant for those configurations experiencing transonic/supersonic conditions, cavitating effects and/or the occurrence of massive turbulence or vorticity fields. The latter concerns, particularly, marine propellers advancing in non-axial flow, that is, in yaw condition during a turning manoeuvre or in cruise motion in case of high-speed propellers fitted to shafts with considerable rake angles [2]; both configurations give rise to massive vortical structures and turbulence phenomena in large zones of the hydrodynamic field where the nonlinear sources of noise may play a crucial role in the noise emission. Therefore, beside the standard thickness and loading noise terms [3], an acoustically-consistent prediction of the propeller hydroacoustic signature needs the inclusion of these contributions. This may be accomplished avoiding cumbersome computations of volume integrals through the solution of the Acoustic Analogy for permeable surfaces surrounding the body and all the corresponding noise sources around it [4]. Following this approach, the evaluation of the overall noise signature is transformed into the application of boundary integral representation (on the permeable surface) for the solution of the FWHE. Thus, the permeable surface assumes the role of acoustic boundary, emitting the noise contributions enclosed by it.

To this aim, accurate and reliable CFD predictions, detecting the sources of sound embedded by the permeable surface, are mandatory. Literature works demonstrate that the Ffowcs Williams and Hawking Equation for permeable surfaces (FWH-P) is nowadays widely used whenever quadrupole noise effects have to be included into the acoustic analysis [5] [6]. However, the unquestionably numerical advantage of this technique is paid in terms of critical issues concerning with the permeable surface. Although the shape is well proven to not be a matter [4], its placement with respect to the embedded noise sources, the end-cap problem and the related different level of accuracy associated to the choice of open or closed surfaces are critical aspects for which a debate is still open in the literature [7]. Some of the authors have discussed these issues in a previous work [8] dealing with the assessment of the FWH-P technique for the prediction of the noise generated by marine propellers and horizontal-axis wind turbines in axial-flow conditions. In that paper, the effects of placement and extension of the permeable surface on predictions are investigated, dealing with the issue of the outflow disk that may be source of inaccuracy.

As a further step of an ongoing activity on this topic, the present paper proposes the analysis of the underwater sound generated by isolated propellers working in non-axial flow condition. In details, a four-bladed propeller model (namely the INSEAN E779A) in yaw condition is investigated from a hydroacoustic standpoint through the FWH-P approach. A DES (Detached Eddy Simulation) [9] hydrodynamic analysis of the propeller is used to determine the sources of noise embedded within the permeable surface. Due to the vortex dynamics developed in the propeller wake, such an approach that combines a URANSE (Unsteady Reynolds Averaged Navier Stokes Equations) modelling to describe the unsteady hydrodynamics close to rigid walls with the direct description of the flow in the wake (the detached vortices), is expected to be effective in capturing the sound sources enclosed by the acoustic permeable surface [3], [10]. A key-point for the application of the FWH-P Formulation is the choice of an optimal permeable surface, whose shape and placement have to be tailored to account for the very complex unsteady vortical structures present in the propeller wake, interacting with each other and inducing flow instabilities. Note that the applied approach is general, in that several of these issues concern also with helicopter rotors in forward flight. In the paper, noise signatures carried-out by the FWH-P approach are compared with the DES-based pressure signals; this is done for acoustic observers in the near field where the above CFD solver, based on the assumption of incompressible flow, is well suited to check the consistency of the FWH-P results [3].
2. Noise Radiation Modelling

Let \( f(x, t) = 0 \) (with \(|\nabla f| = 1\)) identify an arbitrary permeable surface \( S \) moving throughout the fluid domain with velocity \( v \). Under the assumption of negligible entropy changes, the acoustic pressure disturbance outside \( S \), generated by the sources of sound inside and outside it, is governed by the Ffowcs Williams and Hawkings Equation (FWH-P) \([4]\)

\[
\Box^2 p' = \frac{\partial}{\partial t} [\rho_0 \mathbf{v} \cdot \nabla f \delta(f)] + \frac{\partial}{\partial t} [\rho (\mathbf{u} - \mathbf{v}) \cdot \nabla f \delta(f)] \\
- \nabla \cdot [\mathbf{P} \nabla f \delta(f)] - \nabla \cdot [\rho \mathbf{u} \otimes (\mathbf{u} - \mathbf{v}) \nabla f \delta(f)] + \nabla \cdot [\mathbf{T} H(f)]
\]

(1)

where bars denote generalized differential operators, \( \Box^2 = (1/c_0^2)(\partial^2/\partial t^2) - \nabla^2 \) represents the wave operator whereas \( H(f) \) and \( \delta(f) \) are the Heaviside and Dirac delta functions, respectively. In addition, \( \mathbf{u} \) is the local fluid velocity, \( \mathbf{P} = [(\rho - \rho_0) \mathbf{I} + \mathbf{V}] \) is the compressive stress tensor, \( \mathbf{V} \) is the viscous stress tensor whilst \( \mathbf{T} = [\rho(\mathbf{u} \otimes \mathbf{u}) + (\rho - \rho_0)\mathbf{I} - c_0^2(\rho - \rho_0)\mathbf{I} + \mathbf{V}] \) represents the Lighthill tensor. Following the Green function approach presented in \([11]\), in a space rigidly connected with the surface \( S \), the boundary-field integral solution of Eq. (1) reads

\[
p'(x, t) = \int_V [\hat{G} \nabla \cdot \nabla \cdot (\mathbf{T} H)] \, dV(y) - \int_S [(\mathbf{Pn}) \cdot \nabla \hat{G} - (\mathbf{Pn})' \cdot \nabla \partial \hat{G}] \, dS(y) \\
- \rho_0 \int_S [\mathbf{v} \cdot \mathbf{n} \nabla \hat{G} + (\mathbf{v} \cdot \mathbf{n} (1 - \mathbf{v} \cdot \nabla \partial))' \hat{G}] \, dS(y) \\
- \int_S [\rho \mathbf{u}^- \cdot \mathbf{n} \mathbf{u}^+ \cdot \nabla \hat{G} + (\rho \mathbf{u}^- \cdot \mathbf{n} (1 - \mathbf{u}^+ \cdot \nabla \partial))' \hat{G}] \, dS(y)
\]

(2)

In Eq. (2) \( V \) indicates the volume surrounding (and including) the surface \( S \) where the noise sources related to the Lighthill stress tensor are not negligible, \([...]_\partial \) denotes that the kernel of the integral must be evaluated at the retarded emission time, \( \tau = t - \partial \), being \( \partial \) the time required by an acoustic disturbance released from a source in \( y \) to reach the observer point \( x \) at current time \( t \). Furthermore, \( \hat{G} = -1/[4\pi r (1 - M_r)] \) indicates the retarded Green function, \( r = |\mathbf{r}|, \mathbf{r} = x(t) - y(\tau) \) whilst \( M_r = (\mathbf{v} \cdot \mathbf{r})/(c_0 r) \) denotes the surface Mach number along the direction where radiation occurs. In addition, the symbol \((\cdot)'\) denotes time derivative computed in the space rigidly moving with \( V \) whereas \( \mathbf{u}^- = (\mathbf{u} - \mathbf{v}) \), and \( \mathbf{u}^+ = (\mathbf{u} + \mathbf{v}) \). This equation states that the sources of sound enclosed by \( S \) affect the noise signature at \((x, t)\) through surface integral terms whereas the acoustic effect from those sound sources outside \( S \) is due to the volume integral contribution. Thus, if \( S \) is such to include all the volume sources of sound, the contribution from the volume integral vanishes (namely the quadrupole term) and noise computation reduces to the solution of a boundary integral representation, here solved by a zero-th order BEM where \( S \) is divided into quadrilateral panels and \( p' \), \( \mathbf{u} \) and their derivatives are assumed to be piecewise constant. The input data set on the permeable surface (that is pressure and velocity fields) are provided by a prior CFD analysis of the flowfield inside \( S \).

3. Numerical results

In this section the prediction of the noise generated by a marine propeller in open water and inclined-flow condition is addressed by the integral solution of the FWH-P. The hydrodynamic data upon the permeable surface are provided by a fully validated finite volume CFD solver \([12]\); the accuracy of the acoustic analogy-based results is assessed by comparing them with the pressure disturbance directly evaluated by the hydrodynamic solver. Before showing the outcomes of this investigation, two case-studies are first presented for validation purposes. Within the framework of the potential-flow theory, the aeroacoustic field generated by a set of roto- translating pulsating point-sources, along with the noise signals radiated (in air) by a single-bladed propeller advancing
in oblique flow (in the vertical plane) are compared with those coming from the application of the Bernoulli equation, thereafter used as reference result.

**Monopoles**

Let us consider five pulsating monopoles translating at velocity \( v_0 = 180 \, \text{m/s} \) along a direction inclined of \( 10^\circ \) respect to the ground and spinning at angular velocity \( \Omega = 6 \, \text{Hz} \) respect to the vertical direction, describing circles of radius 0.2 m. Referring to the monopole M1 (see Fig. 1), each monopole \( Mk \) \((k = 2, 3, 4, 5)\) is placed on a horizontal plane 0.2 m away from to the previous one and is shifted 72° around the vertical axis (counterclockwise) respect to the azimuthal position of preceding point-source. Density and sound speed of the fluid medium are \( \rho_0 = 1.225 \, \text{kg/m}^3 \) and \( c_0 = 340 \, \text{m/s} \) respectively, whereas the pulsating frequency is equal to \( \Omega \). Following the velocity-potential theory for compressible flows, the pressure disturbance and the surface data for the FWH-P formulation, are evaluated by the Bernoulli equation at given observer positions. To this aim, a cylindrical surface 5.67 m long, co-axial with the direction defined by \( v_0 \), having radius 1 m with end-caps placed in the horizontal plane, is taken as permeable surface \( S \). Such a surface is assumed to translate rigidly at velocity \( v_0 \). Figure 2 depicts the contour-plot of the monopoles induced-pressure pulses upon \( S \) at \( t = 0 \), whilst Figs. 3, 4, 5 propose the comparison between the Bernoulli-based signals and those predicted by the FWH-P solver at observers (co-translating at velocity \( v_0 ) \) whose coordinates are summarized in Table 1. As shown, the agreement between pressure predictions is excellent. In addition, for a single pulsating monopole that moves as described above, Fig. 6 shows the directivity pattern, in the \( YZ \) plane on a circle of radius 2 m, for the first harmonic of the radiated noise spectrum. As expected, the agreement is excellent also in this case.

![Figure 1: Monopoles layout.](image1)

![Figure 2: Acoustic porous surface and instantaneous contour of the induced sound.](image2)

**Single-bladed Propeller in Inclined Flow**

The aeroacoustic behavior of a simplified propeller model, composed of a single rectangular blade 1 m long, having a linear twist distribution ranging from 55° (at the root) to 19° (at the tip), constant chord \( c = 0.1 \, \text{m} \), root cut-off of 0.2 m and NACA 0012 airfoil sections, is investigated. The operative conditions are defined by the horizontal advance ratio \( J = U/nD \) equal to 0.75 and three different angles of inclination (in the vertical plane) of the translating velocity, \((0^\circ, 15^\circ, 30^\circ)\). Symbol \( n = 4.77 \, \text{Hz} \) denotes the blade angular velocity, \( D = 2 \, \text{m} \) indicates the blade diameter whereas \( U \)

---

**Table 1: Microphones position.**

<table>
<thead>
<tr>
<th>x[m]</th>
<th>y[m]</th>
<th>z[m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obs1</td>
<td>0.0</td>
<td>476.22</td>
</tr>
<tr>
<td>Obs2</td>
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<td>-4.76</td>
</tr>
<tr>
<td>Obs3</td>
<td>1.20</td>
<td>0.0</td>
</tr>
</tbody>
</table>
represents the magnitude of the advancing velocity. The permeable surfaces used for aeroacoustic computations are cylinders with generatrix line parallel to the direction of the advancing speed, rigidly translating with the propeller hub. Pressure disturbances at observers co-moving with the propeller hub, as well as pressure and velocity field distributions upon the permeable surfaces are evaluated by combining a fully-validated panel code for unsteady, incompressible, inviscid and irrotational flows around three-dimensional lifting bodies [13], herein extended to the analysis of propellers in arbitrary motion, with the Bernoulli equation. For an advancing speed inclined of $15^\circ$ downward, Figure 7 depicts the lateral view of the pressure map upon $S$ enclosing the blade and the potential wake convected downstream, here limited to three revolutions. Making reference to observers position shown in Fig. 7 whose coordinates respect to a rectangular frame of reference centered at the hub are given in Table 2, Figs. 8, 9, 10 compare the Bernoulli-based converged predictions with those carried out by the FWH-P for axial and inclined advanced speed, respectively. As expected, the agreement is very good.
### Table 2: Nondimensional microphones position.

<table>
<thead>
<tr>
<th></th>
<th>x/D</th>
<th>y/D</th>
<th>z/D</th>
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<tbody>
<tr>
<td>Obs1</td>
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</tr>
<tr>
<td>Obs2</td>
<td>0.0</td>
<td>0.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Obs3</td>
<td>3.0</td>
<td>0.0</td>
<td>4.0</td>
</tr>
</tbody>
</table>

In the following, the hydroacoustic behavior of the INSEAN E779A four-bladed propeller in drifting condition is addressed through the FWH-P approach. The main geometrical features of this propeller model are given in [12]. The propeller moves horizontally in open water at a yaw angle of 20°. The advanced ratio, \( J \), is equal to 0.71 whereas the shaft angular velocity is \( n = 25 \text{ Hz} \). A Detached Eddy Simulation is used for the hydrodynamic analysis of both propeller and flowfield around it [12]. The hydroacoustic analysis is performed for hydrodynamic conditions where the propeller wake structure is fully-developed (converged CFD solution) [12]. Noise signatures evaluated at observers co-translating with the hub are based on the knowledge of the unsteady pressure and velocity field distributions upon a cylindrical acoustic surface \( S \) co-moving with the propeller hub. The hydrodynamic analysis of the vortical/turbulence structures evolution behind the propeller disk [12] guides the optimal placement of \( S \) such to avoid impact phenomena. To comply with this requirement, \( S \) is chosen with generatrix line laying in a horizontal plane and inclined of 13.5° respect to the \( x \) axis. Figure 11 shows a top view of the propeller (rotating about the \( x \) axis and translating at velocity \( U \)), enclosed within three different cylindrical surfaces, 14\( D \) long, with radius equal to 0.8\( D \), 0.85\( D \) and 0.9\( D \), respectively. These surfaces are used to check the convergence of the noise signals, that is, to verify that the volume noise contribution due to the Lighthill stress tensor is well-captured by the surface integral terms. To this aim, the analysis of the unsteady spatial distribution of the Frobenius norm of \( T \) outside them proves that it is negligible respect to the values of \( \| T \|_2 \) inside. For conciseness, Fig. 12 depicts the contour plot of \( \| T \|_2 \) at the beginning of the 15th revolution. Hence, for four observers co-moving with the propeller hub, whose coordinates with respect to a rectangular frame of reference centered at the hub are listed in Table 3, Figs. 13, 14, 15 and 16 show the comparison between the time histories of FWH-P and CFD results (time is nondimensional with respect to the shaft period of revolution). It is well evident that the sound signatures obtained by the three cylindrical surfaces are in very good agreement with the pressure signal provided by the DES computation, even though the results associated to the surface with radius 0.9\( D \) are slightly better over the period of interest. Note that a relevant broadband noise contribution due to turbulence dynamics is present at Obs2, in the disk plane, where the thickness noise is expected to be dominant.
ICSV25, Hiroshima, 8-12 July 2018

<table>
<thead>
<tr>
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<th>x/D</th>
<th>y/D</th>
<th>z/D</th>
</tr>
</thead>
<tbody>
<tr>
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<td>-1.23</td>
<td>0.0</td>
</tr>
<tr>
<td>Obs2</td>
<td>0.0</td>
<td>-1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Obs3</td>
<td>0.97</td>
<td>-0.76</td>
<td>0.0</td>
</tr>
<tr>
<td>Obs4</td>
<td>1.94</td>
<td>-0.53</td>
<td>0.0</td>
</tr>
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Table 3: Nondimensional hydrophones coordinates.

4. Conclusions

The hydroacoustic behaviour of a marine propeller in open water, advancing with a yaw angle, is investigated. A boundary element technique solves the porous Ffowcs Williams and Hawkings Equation in terms of integral representation for the radiated sound. The required input data upon the permeable surface, along with the pressure signals used to assess the accuracy of the FWH-P predictions, are given by a CFD-based analysis of the propeller. In addition, two case-studies concerning a set of roto-translating monopoles and a simplified propeller model moving in axial and oblique flow, respectively, are also presented. Within the context of potential flows, they assess (and
validate the FWH-P solver against analytical/numerical results obtained by the Bernoulli equation. The main considerations are:

• for propellers in non-axial flow, the acoustic surface has to fit the wake structure shed downstream to avoid interactions. Inclined cylinders seem to be well suited;
• whether all acoustic sources are enclosed within the porous surface, the external acoustic field is well predicted as proven by comparisons with analytical, numerical or CFD-based results.
• for the marine propeller in yaw flow, a relevant broadband noise contribution due to turbulence dynamics is present for the observer located in the disk plane where the thickness noise component is expected to be dominant.

REFERENCES


