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Recent advances in the theoretical & experimental analysis of naval unit hydroacoustic performance

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The present paper reviews the experimental and theoretical techniques currently used at CNR-INSEAN for hydroacoustic applications. The theoretical procedure used for hydroacoustic analyses is based upon the Lighthill's acoustic analogy and concerns a hybrid hydrodynamic and hydroacoustic solver. Experimental hydroacoustics regards simultaneous velocity-pressure/visualization-pressure measurements and cross-correlation and conditional techniques. Furthermore, special signal processing techniques are used for the sake of removing unwanted noise contributions and separating the sound and pseudo-sound contributions. Examples of hydroacoustic analyses undertaken by aforementioned theoretical and experimental tools are documented in the paper.

Introduction

In the last ten-fifteen years the technological advances in the research field have allowed to develop experimental and theoretical tools by which improving the understanding even of the more complex mechanisms governing the hydrodynamic and hydroacoustic performance of naval units (i.e. surface ships, submarines, torpedoes). This has widened the horizons of modern research towards complex problems of naval engineering, never tackled before, and, in general, has allowed approaching even the most challenging and difficult demands by shipyards and navies.

The performance assessment and improvement of ships and submarines in beyond-design operations (i.e. propulsors in static and dynamic off-design conditions, effects of the beyond design operative conditions on the ship manoeuvrability and transversal stability) and the reduction of ship/submarine and torpedo susceptibility to detection are worth to be cited among the numerous examples.

The present paper aims at reviewing the potential of the most advanced experimental and theoretical tools developed and currently applied at CNR-INSEAN.

In particular, the capabilities of the above tools will be documented hereinafter with reference to the hydroacoustic research in naval engineering, which represents a challenging and critical task for the sake of mitigating, alterating and assessing ship signature. In fact, unlike aeronautic applications, in which well assessed tools, such as beam-forming e.g., can be used for aeroacustic analyses, in underwater acoustics the larger speed of sound and the occurrence of cavitation make it rather complex and put strict requirements to the choice of the best suited methodology.

At large, hydroacustics problems are faced either by experimentally and numerical methodologies.

On the one hand, computational hydroacoustics (CHA) allows a flexible and cost effective approach to hydroacoustic problems and it is particularly suitable for being integrated within optimization tools for new design solutions. Cons concern the complexity,

the need for massive computational resources and the reliability of the result. In this regard, it is worth noting that simulation results are strongly affected by various parameters such as the numerical algorithm, the computational mesh and the implementation: to accept the results, verification by experiments is always needed.
On the other hand, pros and cons of experimental hydroacoustics techniques (EHA) are basically complimentary to those highlighted for the computational approach (i.e. reliability, faster and practical approach for standard acoustic applications among the pros, limited flow quantities resolved simultaneously, costs, measures contaminated by non-physics related noise contributions such as background noise from the facility and reverberation among the cons). It follows that the choice of the best suited approach is strongly depended on the specific application to which the hydroacoustic analysis is addressed.
The structure of the paper is as follows. Section 2 includes a description of the experimental (§2.1) and theoretical (§2.2) tools used at CNR-INSEAN for hydroacoustic analyses. By the way, some theoretical and experimental studies dealing with the problem of propeller noise will be presented. Finally, Section 4 will summarize the most important conclusions of the paper.

2. Theoretical and experimental tools

2.1 Theoretical approach to hydroacoustics

The theoretical approach to hydroacoustic problems at CNR-INSEAN is based upon the Lighthill's Acoustic Analogy. A synthesis of the adopted approach is schematically reported in Figure 1.
In this approach the computational domain is split into different regions, such that the governing acoustic or flow field can be solved with different equations and numerical techniques. This would involve using two different numerical solvers, first a dedicated Computational Fluid Dynamics (CFD) tool and secondly an acoustic solver. The flow field is then used to calculate the acoustical sources. At CNR-INSEAN the fluid field solution is provided by the following three alternative approaches:

- a surface inviscid flow solver (BEM) with sheet cavitation model implemented
- a field viscous-flow model (RANS)
- a viscid-inviscid hybrid approach (BEM/RANS).

Therefore, the INSEAN hydroacoustic analysis is, so far, limited to no-cavitating flows for propellers and multibody (ship) configurations (by using an unsteady RANSE and BEM code) and to isolated marine propellers affected by sheet cavitation (by using a suitable BEM formulation).

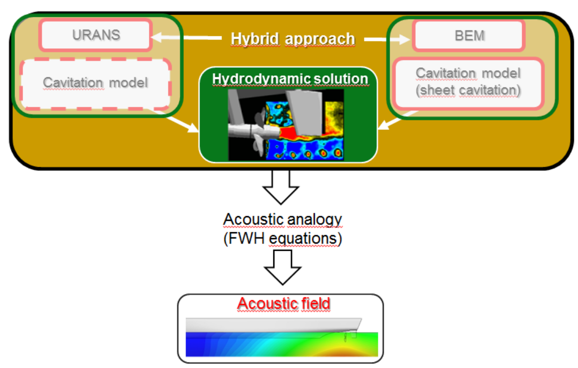

Figure 1. Sketch of the hybrid CFD and CHA approach used at CNR-INSEAN

The acoustical sources are provided to the second solver which calculates the acoustical propagation. The analysis of the acoustic propagation is undertaken through the solution of the Ffowcs Williams-Hawkings (FWH) equation: a rearrangement of the fundamental conservation laws of mass and momentum into an inhomogeneous wave equation, where the different noise generation and propagation mechanisms are identified and expressed by separate source terms.

A simplified representation of the FWH equation is given below:

$$\Box p' = S_1 + S_2 + S_3$$

where:

- p' is the acoustic disturbance
- $\Box = \frac{1}{c_0^2}\frac{\partial}{\partial t^2} - \nabla^2$
- S_1 is the monopole term that is associated to sound waves created by alternately introducing and removing fluid into the surrounding area. This term is basically correlated to the body shape and called thickness noise.
- S_2 is the dipole term, that consists of two monopole sources of equal strength but opposite phase and separated by a small distance compared with the wavelength of sound. While one source expands the other source contracts. The result is that the fluid near the two sources sloshes back and forth to produce the sound. This term is basically correlated to the hydrodynamic loads and called loading noise.
- S_3 is the quadrupole term, that consists of two opposite phase dipoles lying along the same line. This term is basically correlated to the non-linear effects such as turbulence, vorticity, instabilities etc.

The hydroacoustic solver is equipped by scattering model which allows studying the acoustic behavior of complex configurations, like in the case of an installed propeller, without invoking the interactive hydrodynamics to calculate the scattered pressure field on the boundary of the scatterer. This technique is suitable for those naval multi–body configurations where the sources of noise may be considered hydrodynamically independent of the presence of the rest of the configuration.
For a more in-depth analysis of the hydroacoustic model used at CNR-INSEAN refer to e.g. Testa (2008) and Salvatore et al. (2009).
The availability of an effective computational tool, able to characterize the hydroacoustic behavior of a ship, proved to be suitable for a lot of interesting and rather new investigations such as:

- Acoustic tests on isolated and installed propellers at different operating conditions (blade shape, inflow, J/rpm, pitch, etc.)
- Tests on different complex configurations (e.g. surface ships and submarine, weapons)
- Scattering effects of the free surface
- Acoustic signature assessment in maneuvering operations;
- Propagation phenomena far from the body-source
- Cavitation noise.

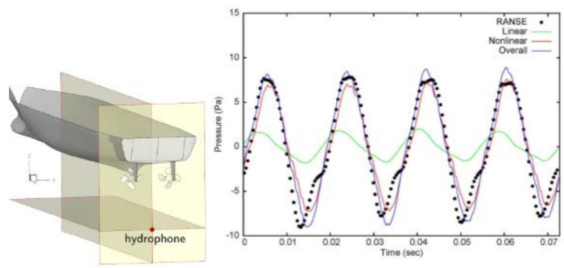

Figure 2. Contribution of the linear and non-linear terms of the FWH equation to the overall noise at the hydrophone location

As an example, results of a numerical investigation on the acoustic field generated by a ship underwater are presented hereinafter. The theoretical approach consisted in coupling an unsteady RANSE code to the hydroacoustic solver. Figure 2 shows the phase locked averaged noise signal as predicted by a virtual hydrophone placed in the vertical symmetry ship plane and close to the propeller disk (left of Figure 2). The result points out 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 (i.e. linear terms of the FWH equation), as to the notable fluid velocity gradients and turbulence released underwater, mainly due to the propeller wake dynamics (i.e. non-linear term of the FWH equation).

As a further example of the effectiveness of the numerical tools, Figure 3 documents the result of a pure linear analysis of the hydroacoustc field at three depths, in the stern region of a ship. The thickness and loading source terms due to the propeller are predominant just in a very limited region around the propeller itself. On the contrary, an appreciable (linear) noise contribution in the far field arises from the hull scattered pressure.

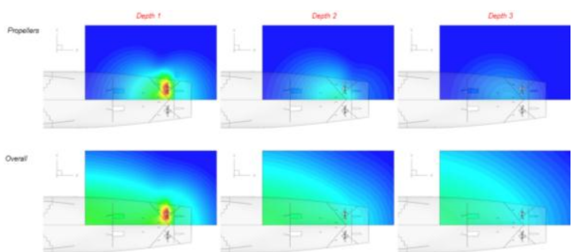

Figure 3. Propeller and overall contributions to the acoustic signature by a pure linear analysis of the hydroacoustic field. Propeller radiated noise is dominant close to the propulsor and reduces more and more with the depth. On the contrary the contribution of the scattered noise keeps about constant.

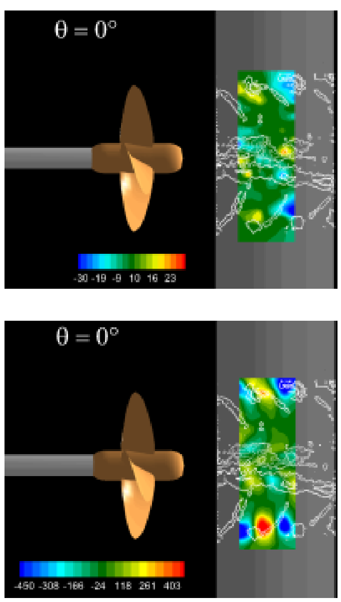

Figure 4. Topology of the shaft (top) and blade (bottom) harmonics of the wall pressure fluctuations on the rudder surface. White lines represent the vorticity field measured by LDV.

2.2. Experimental approaches to hydroacoustics

Experimental hydroacoustic activity at CNR-INSEAN is mainly focused on the development/application of advanced techniques for the noise source identification at model scale level as well as the performance of model scale measurements of the overall noise footprint around given ship and propeller geometries. By the way, advanced post-processing and signal treatment tools, such as advanced time-frequency signal decomposition techniques based on univariate and multivariate wavelet transforms and more standard methods commonly used for reduced order modeling, have been developed to support the hydroacoustic analysis at both the acquisition and the processing stages.
An overview of the tools used for experimental hydroacoustic applications is given hereinafter.

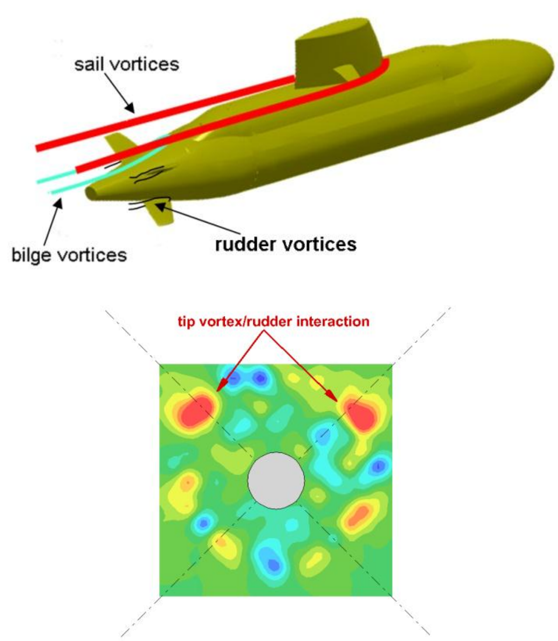

Figure 5. Sketch of the vortical structures that impact on a submarine propeller typically (top). Distribution of the vorticity field just behind the propeller trailing edge: note the interference between the propeller trailing wake and tip vortices with the vortical structures of the inflow (bottom).

- Methodologies for the noise source identification.

Noise source identification tools are based upon simultaneous velocity-pressure/visualization-pressure measurements and special conditioning and cross-correlation techniques.

In conditional techniques, flow measurements and visualizations are filtered according to trigger events identified in the pressure signal (e.g. maximum or minimum peaks of the pressure signal) and then ensemble averaged. This comes out with the topology of the flow field associated with the selected events of the pressure signal through which the corresponding positions of the noise sources can be identified.

An alternative methodology consists of cross-correlating near field flow measurements to a far field pressure signal: regions at which the intensity of the cross correlation is maximum correspond to the location of the noise sources. In both conditional and cross-correlation based techniques, detailed flow measurements are typically undertaken by optical techniques, such as Laser Doppler Velocimetry (LDV) and Particle Image Velocimetry (PIV).

Figure 4 documents an example of a velocity-pressure cross-correlation technique applied to identify and qualify the noise sources in a propeller-rudder interaction. More specifically, the topologies of the shaft and blade harmonics of the wall pressure fluctuations on the rudder surface are correlated with the vorticity field measured by phase locked PIV. The analysis shows that the effect of the tip vortex is the dominant contribution to the wall pressure fluctuations on the rudder. At each harmonic, the tip vortex perturbation has a specific topology, specifically: a monopole-type pattern at the shaft harmonic and a dipole-type pattern at the blade harmonic.

Figure 5 shows the ensemble averaged vorticity field conditioned with the maximum peaks of the pressure fluctuation signal. Conditional analysis points out that the noise sources associated with the maximum peaks of the pressure signal are related to the interaction between the rudders and the propeller tip vortices.

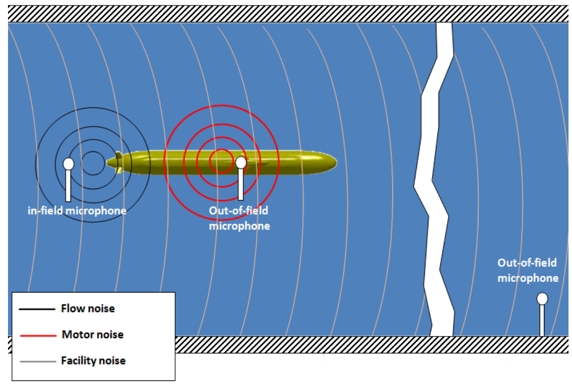

Figure 6. Set up used to remove the background noise from hydroacoustic measurements

- Methoologies for the background noise removal. The removal of unwanted noise source contributions (i.e. background noise and reverberant test sections) is a demanding requirement when noise measurements are performed. The method used to eliminate the contribution of any external noise source to the radiated sound is a general spectral conditioning technique (Felli, 2011). A exemplifying sketch of the set up used for the purpose of removing the background noise is shown in Figure 6.

The output of the signal acquired by a given in-field hydrophone p(t) can be decomposed in the contribution of the underlying deterministic signal u(t) (i.e. the physical signal related to the ship/propeller radiated noise in ideal-noise free condition) and any extraneous “non-physical” noise n’(t) (e.g. background noise generated by the engine, facility noise).

If a microphone/hydrophone is put far from the measurement locations, i.e. at the ceiling of test section, inside the model close to the motor, it will measure only the background noise signal n(t) (i.e. out of field sensor).

The autospectrum of the background noise filtered signal (i.e. G_{uu}) by the in-field sensor is determined once known the autospectrum function of the in-field sensor (i.e. G_{pp}) and the coherence function between the out-of-field and the in-field signals (i.e. γ_{np}), as follows:

$$G_{uu}(f) = (1 - \gamma_{np}^2(f))G_{pp}(f)$$

As an example Figure 7 documents the removal of the contribution of the motor noise from the autospectrum of a pressure signal acquired in the wake of a propeller.

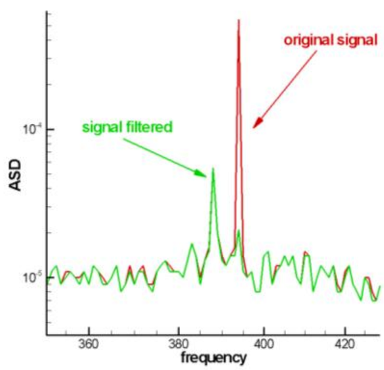

Figure 7. Motor noise removal from the autospectrum of a pressure signal acquired in the wake of a propeller.

- Methodology for the isolation of the sound and pseudo sound components

When a measurement of fluctuating pressure is performed in the near-field, the acoustic contribution is buried by the hydrodynamic one and it is indistinguishable by a single hydrophone signal. The problem of separating acoustic (sound) from hydrodynamic pressure pseudo-sound) is overcome through the application of a proper filtering procedure based on the application of wavelet transform to experimental data (Grizzi and Camussi, 2012).

A sketch of the method is reported in Figure 8. The main idea of the method relies on the evidence that, despite the acoustic counterpart, hydrodynamic pressure fluctuations are intermittent and localized in time and thus compress well over a wavelet basis. The hydrodynamic and acoustic components can then be extracted from a pressure signal by selectively filtering the wavelet coefficients and by the inverse transform of the resulting filtered coefficients set. The separation between acoustic and hydrodynamic pressure is accomplished by selecting a threshold whose amplitude is determined on the basis of the pressure perturbation propagation velocity. This quantity is computed from the maximum of the cross–correlation between the filtered components of two pressure signals measured simultaneously.

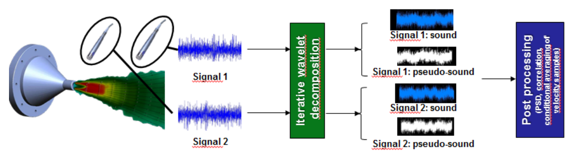

Figure 8. Technique for separating the sound and pseudo sound contributions from pressure measurements.

The application of the technique therefore requires the simultaneous acquisition of pressure time series from two hydrophones positioned close to each other in the near field. Figure 9 shows the topology of the velocity-pressure cross correlation peak after separating the sound and pseudo-sound components. The topologies of the sound and pseudo sound based cross-correlation fields result different and allow highlighting the location of the acoustic and hydrodynamic sources.

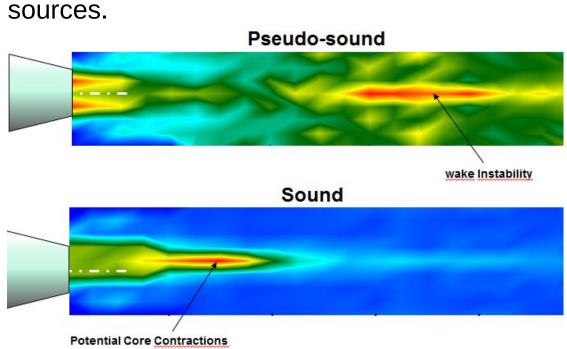

Figure 9. Velocity-pressure cross-correlation field using pseudo-sound (top) and sound (bottom) contributions.

Conclusions

The opportunity to mitigate, control and mask the acoustic signature from a vessel or a submarine unit represents a topic with a high strategic capacity that has implied a rising interest on detailed experimental and numerical investigation techniques of the propulsor hydro-dynamics and hydro-acoustics, to be used to support new design approaches. In the last decade, the technological advances in the research field at CNR-INSEAN have resulted in advanced experimental and theoretical tools which have shed light into the fundamental mechanisms governing the hydrodynamic and hydroacoustic performance of a naval unit. However, the hydroacoustic research has still some open issues so far, especially for what concerns cavitation and bubbly flow effects on the acoustic signature. The detailed investigation into these aspects still represents a challenging task for both theoretical and experimental research.

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