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Experimental approaches for the diagnostics of hydroacoustic problems in naval propulsion

M. Felli *, M. Falchi, G. Dubbioso

CNR-INSEAN, National Research Council, Maritime Research Centre, Italy

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ABSTRACT

Current standard experimental methodologies in hydro-acoustics rely on far-field measurements that enable the characterization of the spectral properties and the determination of the sound pressure level with good precision but fail in identifying accurately the flow phenomena at the origin of sound generation and radiation. The present paper reviews two "unconventional" approaches to address the diagnostics, analysis and solution of hydroacoustic problems in naval engineering experimentally. The first approach, based on direct pressure fluctuation measurements combined with detailed flow measurements in the proximity of the noise source, provides a direct estimate of the flow phenomena at the origin of sound generation and emission. The second approach is a relatively recent strategy to investigate the sources of acoustic noise in the aeronautical field and concerns the use of volumetric techniques, such as Tomographic PIV (Elsinga et al., 2006), in combination with acoustic analogies. The abilities of the two approaches are investigated with reference to the analysis of the noise sources in some case studies consisting of an isolated propeller, a propeller operating in the wake a surface ship, and an open-water propeller-rudder system. Both approaches are shown to enable the physical interpretation of the potential mechanisms of noise generation and emission from a naval propeller. For example: (i) the combined employment of Tomographic PIV measurements with the Powell's acoustic analogy proved the dominant contribution of the tip vortices to the radiated far-field noise in non-cavitating conditions and showed the different directivity of the quadrupoles associated with the tip vortex, the trailing wake and the hub vortex perturbation; (ii) the use of simultaneous near- and far-field measurements combined with cross-correlation techniques revealed the direct relationship between the acoustic perturbation and the Azimuthal gradients of the blade hydrodynamic loads for an installed propeller in non-cavitating conditions; (iii) the application of a filtering procedure to separate the sound and pseudo-sound contributions from recorded near-field pressure fluctuation signals highlighted the different mechanisms underlying the acoustic and hydrodynamic perturbation in a propeller-rudder system.

1. Introduction

Mitigation and control of the ship noise footprint are issues of increasing importance for the international shipbuilding industry, due to the increasingly demanding rules and classification standards that must be complied before ship delivery both in civil and military fields (Carlton and Vlasic, 2005). In fact, the dramatic increase of the underwater noise pollution, estimated by 3-6 dB/year since the 60's, created the need to mitigate ship noise, whose levels represent nowadays a dramatic threat to the survivability of the marine biodiversity and the sustainability of the maritime transport (Hildebrand, 2004). On the other hand, reduction of ship/submarine susceptibility to detection has been a relevant issue in naval field and has concerned many efforts to develop effective acoustic signature mitigation, control and alteration solutions.

In order to meet these requirements, a major breakthrough in ship design and operation is needed by the industry and research community, thus complying with the new standards for safer and more sustainable shipping as well as with the rigid performance requirements in the naval field. In particular, research is needed to address the two-fold task of developing effective tools to support the diagnostics and the design of ships on one hand, and to improve the understanding of the fundamental underlying mechanisms of the noise generation and radiation phenomena, on the other hand.

* Corresponding author
E-mail address: mario.felli@cnr.it (M. Felli).

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Nomenclature

ρ_0	reference density
ν	kinematic viscosity
$x^{\rightarrow}$	position vector of observer
$y^{\rightarrow}$	position vector of the noise source
$u^{\rightarrow}$	velocity vector
$\omega^{\rightarrow}$	vorticity vector
$L^{\rightarrow}=\omega^{\rightarrow}\times u^{\rightarrow}$	Lamb vector
t	time
c_0	speed of sound
τ	time shift between source emission and receiver
τ'	retarded time $\tau'=t-\tau$
θ	Azimuthal position of the reference blade
$\Box^2$	wave operator
M	Mach number
Re	Reynolds number
p'	pressure fluctuation
ψ'	generic flow field variable within the source region
$\boldsymbol{\sigma}$	r.m.s of field variable in the source field
$S(\boldsymbol{x},\boldsymbol{y},\tau)$	cross-correlation function
$<\ldots>$	average operator
N	number of conditional events
δ	Dirac function
T^*	thresholding level in the conditional analysis
h^*	resolution scale in the wavelet transform
R	propeller radius

Current standard experimental investigations in hydro-acoustics rely on the localization of noise sources by far field hydrophone arrays and advanced signal processing capabilities for sound recognition, underwater sound source localization and motion tracking (Brooks and Humphreys, 2006). For example, beam-forming is an effective measurement technique in which the identification of the noise sources is undertaken on the basis of the phase shift among microphone signals organized in large arrays and positioned in the acoustic far field. This experimental approach has the advantage to deal directly with the acoustic field, enabling the characterization of the spectral properties and the determination of the sound pressure level with a good precision. The drawback lies both in the non-accurate localization of the noise sources and in the lack of information about the flow phenomena at the origin of sound generation and emission. For example, beam-forming is only able to roughly determine the location of the sound sources underwater but cannot provide any information about their nature.

Accurate diagnostics of the noise source localization and the identification of the physical causes of the noise generation and emission phenomena require different approaches that are able to

- provide local information on the acoustic pressure distribution, complementary to remote measurements by phase hydrophone arrays,
- establish a direct connection between the hydro-acoustic problem and the flow phenomena at the origin of noise generation and radiation.

This information is necessary to implement effective design and operational measures for the mitigation, control and alteration of the noise footprint of marine applications.

The present study deals with novel experimental methodologies for the identification and analysis of the hydro-acoustic mechanisms of perturbation in a naval system that have been developed and successfully applied at CNR-INSEAN in the last ten years. These methodologies refer to two different approaches:

- Direct approach: The identification of the noise emission and propagation mechanisms is based upon direct pressure fluctuation measurements in the proximity of the noise source and/or in the acoustic far field. The perturbation induced by the passage of eddy structures involves the pressure signals to be pre-processed through a signal decomposition technique that is able to filter out the hydrodynamic contribution from the near-field pressure fluctuation signals (Felli et al., 2014). Usually, hydrophone measurements are performed in combination with detailed flow measurements in the source region by means of Hot Film, Laser Doppler Velocimetry (LDV) or Particle Image Velocimetry (PIV). Simultaneous pressure and velocity measurements permit the conditional analysis of the flow topology with respect to acoustic pressure fluctuations and, thus, allow to directly link acoustic waves with specific flow events.
- Indirect approach: The main idea behind this approach is to establish a direct connection between the hydro-acoustics problem and the flow phenomena at the origin of noise generation (see Jordan and Gervais, 2008), similarly to what is done by Computational Hydro-Acoustics (CHA) when based on the solution of the fully 3D unsteady Navier-Stokes equations (Ianniello et al., 2014). Unlike in the direct approach, the solution of the hydro-acoustic problem is, then, relied indirectly on quantitative field measurements able to fully describe the unsteady flow behavior and on the application of acoustic analogies in which the source term is formulated in terms of vorticity (e.g. Powell, 1964). This involves the use of a time resolved velocimetry technique capable of resolving all the velocity gradients at an instant for the evaluation of the integrand terms in the analogies.

In this paper we present an overview of the above approaches, with an emphasis on specific applications related to naval propulsion. The objective is highlighting the effectiveness of these approaches to address acoustic problems in towing tanks and other hydrodynamic facilities, at both diagnostics and performance assessment level.

The paper is organised as follows. In Sections 2 and 3 we endeavour to detail the two approaches. The indirect approach is documented in Section 2, in which acoustic analogies are recalled to explain the relation between flow structures and acoustic sources. In particular, attention is here paid to describe the major issues related to the application of volumetric techniques to model hydrodynamically generated sound through the use of the Powell's acoustic analogy (Powell, 1964). Section 3 deals with the direct approach describing the methodologies used to correlate and condition near-field flow measurements with far-field acoustic signals as well as to separate out the acoustic and the hydrodynamic contributions in the near field pressure fluctuation signals.

As an example of indirect approach, Section 4.1 documents a state-of-the-art application to a propeller wake measurement by Tomographic PIV, focusing on the identification of the noise sources by the combined use of a volumetric technique with the Powell's analogy. Section 4.2 reports two illustrative applications of the direct approach relative to the study of a surface ship