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Prediction of submarine scattered noise by the acoustic analogy

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ABSTRACT

The prediction of the noise scattered by a submarine subject to the propeller tonal noise is here addressed through a non-standard frequency-domain formulation that extends the use of the acoustic analogy to scattering problems. A boundary element method yields the scattered pressure upon the hull surface by the solution of a boundary integral equation, whereas the noise radiated in the fluid domain is evaluated by the corresponding boundary integral representation. Propeller-induced incident pressure field on the scatterer is detected by combining an unsteady three-dimensional panel method with the Bernoulli equation. For each frequency of interest, numerical results concern with sound pressure levels upon the hull and in the flowfield. The validity of the results is established by a comparison with a time-marching hydrodynamic panel method that solves propeller and hull jointly. Within the framework of potential-flow hydrodynamics, it is found out that the scattering formulation herein proposed is appropriate to successfully capture noise magnitude and directivity both on the hull surface and in the flowfield, yielding a computationally efficient solution procedure that may be useful in preliminary design/multidisciplinary optimization applications.

1. Introduction

The prediction of hull-pressure fluctuations and flowfield noise induced by screw-propellers in behind-hull conditions are of primary interest for civil and military applications, in that, sound scattering due to the interaction between hull surface and acoustic waves emitted by the propeller(s) may be relevant. Theoretically, sound scattering occurs when an obstacle (scatterer) is present in the path of an acoustic wave and produces secondary sound spread in a variety of directions. Under the assumption that the wavelength of the impinging sound is comparable with a characteristic size of the scatterer, the acousto-structural interaction causes a re-distribution of the energy content of the impinging wave into reflected and diffracted secondary waves that may remarkably alter magnitude, waveform and directivity of the overall noise field, on both hull surface and in the flowfield, with respect to the unbounded space propagation. Sound scattering analysis is a complex matter, involving propeller/hull hydrodynamics and hydroacoustics, hull structural dynamics and acousto-structural interactional phenomena. The issue is relevant for civil applications for what concerns noise regulations and the impact on marine mammals; it plays a crucial role for submarines as their detection and classification is mostly due to the radiation of the sound energy towards the enemy units. In the low-frequency range (less than 200 Hz) dominating the sound spectrum at large

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distances from the hull, a significant part of submarine radiated noise is generated by propellers; they emit sound about 30–50 dB greater than the other sources of noise, with a spectrum dominated by distinctive tonal contributions due to high unsteady blade-loads induced by the flow distortions of the upstream wake and periodic impacts of vortical structures against the blades (*i*.e., bilge vortices, rudder horseshoe vortices and corner vortex originating in the hull-sail intersection region) [1]. Even though the need of minimizing propeller-induced noise has led towards complex sickle-shaped blade configurations to reduce any coupling with the incoming flow, the design of an acoustically *stealth* submerged vehicle requires the analysis of the whole configuration to capture the hull-scattered sound when it is impinged by the noise hydrodynamically generated by the propeller(s). The wide literature concerning sound scattering problems (see, for instance, [2–6]) shows that the scattered pressure field is typically predicted through linear approaches based on boundary integral formulations solving the Helmholtz equation for the velocity potential or the acoustic pressure. Beside them, alternative formulations based on the linear version of the Ffowcs Williams and Hawkings Equation (FWHE) have been proposed [7–10]. These extend the use of the acoustic analogy to scattering problems either through time-domain approaches [8] or frequency-domain methodologies [7,9,10]. However, the number of literature papers on underwater noise facing the problem of hull sound scattering in hull-propeller configurations is limited. Hydroacoustic investigations on whole configurations typically focus on the propeller system, hydrodynamically affected by the presence of the hull (see, for instance [11]). Among the available works, Ianniello et al. [12] propose a physically-consistent approach, not very common for marine problems, to tackle the hydroacoustic analysis of a fully-appended hull in steady motion, propelled by rotating subcomponents; noise computation is decoupled from flow simulation: *all* hydrodynamic sources of sound are first detected through a CFD (Computational Fluid Dynamics) analysis of the whole configuration whereas noise propagation in the flowfield is then described by the acoustic analogy for permeable surfaces [13]. In this kind of simulation, the hydrodynamic solver provides an *overall* description of the flowfield around the whole configuration and inherently captures any mutual interaction among pressure disturbances generated by different ship components (propeller, hull, rudder, appendages, etc); hence, hull scattering effect prediction becomes a hydrodynamic issue instead of a hydroacoustic one. Although well-posed, such a hybrid approach is CPU-time demanding and thus, not compatible with pre-design stages and optimization studies that require fast and reliable simulations. However, for those configurations and operating conditions where a primary source of noise may be (clearly) identified, and under the assumption that the impinging pressure field is independent of the presence of the scattering surface(s), the overall noise field may be decomposed into incident and scattered components and an acoustic scattering modelling may be used, thus avoiding time-consuming computations. Within the limits of this approach, the acoustic scattering analysis may be conceived as a two-step problem, where the primary source of noise is seen as *frozen*, thus generating an incident pressure field which may be computed by a *prior* (hydrodynamic and hydroacoustic) analysis as if it were isolated, whilst scatterer bodies are involved in the second stage of the problem, concerning with the scattered noise prediction. Aeronautical configurations are well suited for this kind of approach [14,15]; differently, submarines, ships or vessels, where the primary source of noise is undoubtedly the propeller, inherently suffer of the mutual hydrodynamic interactions between propeller(s) and turbulent/vorticity-fields released by the fully-appended hull. Nevertheless, in absence of relevant blade-vortex interactions, hull–propeller hydrodynamics may be limited to consider the hull wake incoming to the isolated propeller in unbounded fluid domain, thus allowing the application of a scattering formulation as previously described. In this context, Kehr and Kao [6] propose a time-domain iteration method to predict ship hull and free surface acoustic scattering effects on propeller noise due to unsteady sheet cavitation and fluctuating forces arising when the propulsor operates in the nonuniform ship wake. The same scattering formulation is applied in Wei et al. [16] to capture the effect of a submarine hull on propeller non-cavitating noise; a suitable CFD analysis of the isolated propeller in the hull wake, combined with the FWHE (limited to thickness and loading noise terms) predicts the incident radiated sound field. In van Wijngaarden [17] a chain of computational methods is proposed for the prediction of the ship hull pressure fluctuations induced by a cavitating propeller: a Boundary Element Method (BEM) for the acoustic potential satisfying the Kirchhoff-Helmholtz equation is used to capture the scattering effects from hull and free surface once the wake field and propeller noise source strengths are known.

In this framework, the need to gain a deeper insight into submarine noise generation mechanisms has inspired the present paper that proposes the non-standard pressure-based formulation presented in Gennaretti and Testa [9] for the prediction of non-cavitating propeller tonal noise scattered by a submarine in cruise motion. Specifically, by renouncing to model those tonal noise components associated to periodic impacts of vortical structures against propeller blades, the overall pressure field is computed by a frequency-domain boundary integral solution of the linear version of the FWHE, solved by a BEM scheme, where: i) the nonuniform propeller onset flow is assumed to be the hull nominal wake, known from a devoted CFD analysis; ii) the incident pressure field, on the scatterer and in the flowfield around it, is evaluated by a prior hydrodynamic/hydroacoustic analysis of the isolated propeller working in the previously defined nonhomogeneous onset flow; iii) scattered pressure distributions, on the hull and in the flowfield, are obtained by the definition of suitable acoustic transfer functions matrices between the incident and the scattered sound. The submarine is assumed to operate in deep water, hence no scattering contributions from bottom and free surfaces are considered. This formulation has been applied to helicopters [18,19] and propeller-driven aircraft configurations [20,21], whereas an early attempt of application to a hull-propeller system has been addressed in Ref. [22]. Akin to [16], in Refs. [18–22] the impinging aero/hydro-borne sound comes from the 1A Farassat formulation [23] once the unsteady blades pressure field is known from an aero/hydro-dynamic analysis of the rotor/propeller system. Differently, in order to capture those potential wake-induced pressure contributions, only indirectly modelled by the loading-noise term of the FWHE, in the present work the incident pressure fluctuations are predicted by a fully-validated potential-based panel method, combined with the Bernoulli equation for incompressible flows [24]. According