ARTICLE IN PRESS

International Journal of Heat and Fluid Flow xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

journal homepage: www.elsevier.com/locate/ijhff

Hydroacoustic noise from different geometries

M. Cianferra[*,a], V. Armenio[a], S. Ianniello[b]

[a] University of Trieste, Engineering and Architecture Department, Trieste, Italy
[b] CNR-INSEAN, Marine Technology Research Institute, Rome, Italy

ARTICLE INFO

Keywords:
Hydroacoustic
Ffowcs Williams and Hawkings analogy
LES
Turbulent flows

ABSTRACT

Turbulent flow around bluff bodies generates pressure fluctuations which propagate as acoustic waves. Differences in the shape of a body can affect frequencies and amplitudes of the propagating pressure signals. In the present work three elementary geometries (sphere, cube and prolate spheroid), immersed in a uniform water flow, are examined in order to analyze the differences of the resulting hydroacoustic fields. The turbulent flow at $Re_A = 4430$ (based on the cross-sectional area of the bodies) is reproduced through wall-resolving Large-Eddy Simulation and the hydroacoustic far-field is analyzed by adopting the Ffowcs Williams and Hawkings analogy. The quadrupole term of the acoustic equation is first reformulated in the convective form and then solved through direct computation of the volume integrals. This procedure is found possible in hydrodynamics where the speed of sound is very large and the flow velocities are small. In spite of the fact that the frontal section of the bodies has the same area, the analysis shows that a streamlined body is able to produce a pressure signal one order of magnitude lower than that generated by a bluff geometry. The separate analysis of the loading noise and of the quadrupole one has shown that the former is larger than the latter in case of 3D-shaped bluff body (sphere and cube), whereas the opposite is true in case of a streamlined body. A preliminary analysis between the case of an elongated square cylinder and a cube, shows that the persistence of a two-dimensionally shaped wake when compared to a three-dimensional one contributes to increase the quadrupole part of the radiated noise.

1. Introduction

Fluid dynamic noise constitutes a serious issue in a number of engineering applications and growing attention is being paid toward new generation mathematical models able to perform reliable noise predictions (see, among the others, Carlton and Vlasic, 2005 and Murphy and King, 2014).

Since sound represents propagation of pressure/density disturbances, in principle the Navier–Stokes equations for compressible flows should be solved for the study of near and far-field sound propagation (this is known in literature as direct method). However, few studies of this kind are available in literature, mostly limited to 2D cases or elementary configurations (see, for example, Inoue and Hatakeyama, 2002; Marsden et al., 2008), because the use of a direct method may be unpractical for two main reasons. When the fluid-dynamic field is incompressible (Mach number smaller than 0.3 and, in general, all main problems concerning the generation and propagation of noise underwater), the problem is substantially elliptic, and the use of numerical methods suited for hyperbolic problems (like the compressible flow field) may produce an ill-conditioned system of equations whose numerical solution is practically impossible; second, the computational domain normally used for a computational fluid dynamic (CFD) solution is necessarily limited in size and much smaller than the distance where the knowledge of the hydrodynamic noise is usually required. To overcome these problems, hybrid methods have been developed in the past (mainly for aeronautical configurations) and nowadays they constitute the standard numerical approach in the acoustic community. The hybrid method allows to decouple the fluid dynamic problem from the acoustic one. The fluid dynamic field is determined using CFD solutions obtained in the flow regime of interest (either incompressible or compressible) within a suitable computational domain. The acoustic field is obtained using an acoustic analogy, where the conservation laws are re-written as an inhomogeneous wave equation and the flow is treated as a collection of noise sources. The coupling between the fluid dynamic part of the problem and the acoustic one is carried out using the instantaneous fields obtained in the CFD solution as input data for the acoustic equation. The most important advantage of the hybrid method stands in the fact that, starting from a confined fluid dynamic domain, the acoustic solution can be projected onto the far field, at any point of interest. Further, due to the presence of different source terms, the inhomogeneous wave equation provides a simple identification of the dominant source mechanisms taking place in the flow.

* Corresponding author.
E-mail addresses: marta.cianferra@phd.units.it (M. Cianferra), vincenzo.armenio@dia.units.it (V. Armenio), sandro.ianniello@cnr.it (S. Ianniello).

https://doi.org/10.1016/j.ijheatfluidflow.2017.12.005
Received 5 May 2017; Received in revised form 22 October 2017; Accepted 16 December 2017
0142-727X/

Please cite this article as: Cianferra, M., International Journal of Heat and Fluid Flow (2017), https://doi.org/10.1016/j.ijheatfluidflow.2017.12.005

Different formulations of the equations for the acoustic field have been developed in literature. In Ffowcs-Williams and Hawkings (1969), a comprehensive formulation was given (hereafter referred to as FW-H equation) in which a body in relative motion with respect to the surrounding fluid can be considered.

The integral form of the FW-H equation consists of a sum of surface and volume integrals, which are commonly identified as dipole and quadrupole terms respectively. In literature, the direct evaluation of the quadrupole noise terms has rarely been carried out for two main reasons: It is considered very expensive from a computational point of view; it may be affected by computational noise in case of sharp discontinuities in the pressure/density field occurring in the fluid dynamic compressible regime. In addition, in the aeroacoustic literature (such as in studies of helicopter noise), the non-linear quadrupole terms are usually considered negligible in comparison to the linear ones, namely, the loading noise associated to the presence of a body and the thickness noise related to its own movement.

However, in their fundamental work (see for example Farassat and Brentner, 1988; Farassat and Brentner, 2003), the authors pointed out the significant role played by the quadrupole terms in the radiated noise. In particular, they reformulated it for three different regions (boundary layer, shock surfaces and tip vorticity/wake) in such a way to obtain surface integrals instead of volume integrals. They provided detailed considerations on the fact that the quadrupole noise may behave as thickness and loading noise and, for example, suggested that *the tip vorticity effect can be converted into a line integral along the vortex line* and that *the blade wake contribution can be written in such a way that only the gradient of velocity normal to the wake appears*. Further, the authors emphasized the need of using accurate fluid-dynamic data and fine spatial resolution for a reliable reconstruction of the radiated noise.

For all reasons mentioned above, the quadrupole noise is generally formulated through an alternative approach, known as *porous formulation* (see DiFrancescantonio, 1997). This method consists in moving the surface integrals from the body surface over an external *porous* radiating surface, embedding the body and the whole fluid region characterized by nonlinear sources. In Cianferra et al. (2017) a comparison between the porous method and the direct evaluation of the quadrupole terms was carried out. When the porous method is applied without corrections that eliminate the end-cap problem (namely the spurious noise generated by vorticity crossing the porous surface, see Nitzkorski and Mahesh, 2014) the direct computation of the volume terms provides the most reliable and accurate results. However, the authors also pointed out that the direct evaluation of volume integrals is feasible from a computational point of view when times delays are negligible, that is, when a collection of noise sources can be considered as to propagate instantaneously (this concept will be exploited in the next Section). In general, a motionless/slowly moving body immersed in a stream of water belongs to this case, thus, in most cases in hydrodynamics, the source noise can be assumed compact.

In the recent years, the acoustic analogy has been used in several applications in literature. Among the others, studies of realistic geometries for marine applications were carried out by Ianniello et al. (2013), Li et al. (2015), Lidtke et al. (2015, 2016) and Bensow and Liefvendahl (2016). These works focused on the underwater propeller noise, employing the FW-H porous formulation in conjunction with fluid dynamic fields obtained solving the Unsteady Reynolds Averaged Navier–Stokes (URANS) equations or using Detached Eddy Simulation (DES).

More fundamental studies, focused on hydrodynamic noise generated by simple-shape objects, were carried out by, among the others, Lockard et al. (2007), Pando et al. (2014) and Gloerfelt et al. (2005). Specifically, Lockard et al. (2007) performed experimental and numerical (URANS) studies of a tandem cylinder configuration. Extensive comparisons with the experimental data were carried out to assess the ability of the computations to simulate the details of the flow and the radiated noise. Their acoustic analysis was based on the method described in Lockard (2002), where the author compared a frequency domain solution method of the FW-H equation with the (porous) retarded-time formulation.

Pando et al. (2014) performed direct numerical simulations of the compressible Navier–Stokes equations and showed good agreement with previous experimental and numerical investigations on noise radiated from a NACA0012 airfoil.

Gloerfelt et al. (2005) studied the flow around a circular cylinder. Curles formulation was analytically and numerically compared to a formulation based on an exact Greens function tailored to a cylindrical geometry.

In spite of the geometrical simplification, the study of hydrodynamic noise generated around simple bodies has proved to be significant, because it can exploit fundamental aspects of the topology of the flow field which, in turn, rules generation and propagation of hydrodynamic noise.

To the best of our knowledge, a systematic study of noise generated by elementary geometries different from those mentioned above, has not been carried out, especially for underwater problems. In the present paper, we give a contribution to this aspect, considering three simple, yet significant, geometries in the turbulent regime: A sphere, a cube and a prolate spheroid at zero angle of attack. The sphere produces massive separation at the rear of the body and a wake characterized by overlapping of vortex shedding and energetic turbulence generated by a shear layer; the cube behaves likewise the sphere, apart the presence of sharp corners which may contribute to noise generation; the prolate spheroid aligned with the main current, develops a small separation region in the trailing edge region and a wake much less intense than in the other cases. Finally, a preliminary comparison between the noise generated by the cube and that given by a 2D-shaped geometry (the elongated square cylinder studied in Cianferra et al., 2017) is carried out, to evaluate the contribution of the nonlinear term to the far-field noise propagation in case of 3D and 2D massive separation respectively.

For sake of comparison, the Reynolds number, based on the square root of the frontal area, the uniform inlet velocity, and viscosity, is $Re_A = \sqrt{A}\,U_0/\nu = 4430$ for the three objects. The fluid dynamic field is solved using wall-resolving Large Eddy simulation (LES), able to reproduce the energetic part of the energy spectrum, which mostly contributes to the radiated noise (see Piomelli et al. (1997) and Seror et al. (2000)). The acoustic field is reconstructed by using the FW-H equation, computing the non-linear quadrupole terms through direct volume integration. The main contributions of the present paper to the literature are: Evaluation of the far-field noise for three significant geometries; application of the direct volume method to the evaluation of the quadrupole term; a preliminary estimation of the contribution of 2D- and 3D-shaped wakes to the far-field noise; wall-resolving LES-generated database of fluid-dynamic data available to the scientific community for successive studies.

The paper is organized as follows. Section 2 provides a concise theoretical background, for both fluid dynamic (Section 2.1) and acoustic (Section 2.2) models; Section 3 contains the general features of the numerical setup. Section 4 contains: Validation of the results for the fluid dynamic field on the sphere together with a test on the acoustic model adopted (Section 4.1); a comparison of the acoustic far-field generated by the three different objects (Section 4.2); a comparison of radiated noise in case of 2D- and 3D-shaped wakes (Section 4.3). Concluding remarks are given in Section 5.

2. The mathematical formulations

Both fluid dynamic and acoustic models are based on the