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Investigation and modelling of the turbulent wall pressure fluctuations on the bulbous bow of a ship

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ABSTRACT

For the effective operation of sonar systems mounted inside the bulb of fast ships, it is important to reduce all the possible noise and vibration sources that radiate noise and interfere with sonar sensor response. In particular, pressure fluctuations induced by turbulent boundary layers on the sonar dome surface represent the major source of self-noise for on-board sensors. Reliable calculations of structural vibrations and noise radiated inside the dome require valid statistical descriptions of wall pressure fluctuations beneath the turbulent boundary layer. Previous research about wall pressure fluctuations deals with equilibrium turbulent boundary layers on flat plates in zero pressure gradient flow, for which scaling laws for power spectral densities and empirical models for the cross spectral densities are well established. On the contrary, turbulent boundary layers on bulbous bow exhibit the combined effects of three-dimensionality, streamline and spanwise curvatures and pressure gradients. In order to collect information about realistic configurations, wall pressure fluctuations were measured in an experimental campaign performed in a towing tank; data were collected at two different locations along a large scale model of a ship bulb and their spectral characteristics were investigated in terms of auto and cross spectral densities. Mean flow parameters of the boundary layer, required in the analysis, were obtained by a finite volume code that solves the Reynolds Averaged Navier Stokes Equations. The applicability of classical scaling laws for pressure spectra on zero pressure gradient flat plate was investigated, together with the spatial characterization of the wall pressure fluctuations in the space-frequency domain; parameters of some semi-empirical models available in the scientific literature were tuned to fit the measured pressure field.

1. Introduction

Sonar systems installed on surface ships are usually located in a streamlined and acoustically transparent dome projecting below the keel or in the fore part of the hull (bulbous bow). Since dome vibrations may significantly affect the effective operation of the sonar system, a detailed characterization of the main sources of self-noise for the on-board instruments is of fundamental importance. While machinery and propeller noises are prominent contributors to sonar self-noise at slow speed, flow-induced structural noise constitutes the major source at high speed. In particular, the fluctuating pressure in the turbulent boundary layer (often called “pseudo-sound”) causes structural vibrations and noise radiation inside the dome and can deteriorate sonar system efficiency.

Although in the last 40 years wall pressure fluctuations (WPF) induced by turbulent boundary layer (TBL) have received great

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attention by the research community, most fundamental investigations were limited to simplified geometries (flat plate and cylinder) and ideal flow conditions (i.e. two dimensional equilibrium boundary layer with zero pressure gradient) (Bull, 1996). On the contrary, the flow around a bulbous bow presents relevant peculiarities, because the boundary layer is three-dimensional and the surface has streamwise and spanwise curvatures and pressure gradients; also free surface effects cannot be neglected. Moreover, a not negligible fraction of the boundary layer can be laminar, which is followed by a transition region characterized by strong instability.

The accurate evaluation of WPF would require direct numerical simulation (DNS); as well known, DNS is still unfeasible for realistic high Reynolds number flows, for which Reynolds number based on momentum thickness $Re_\vartheta \sim 10^5$ (Magionesi et al., 2012). In practice, DNS is limited to simple configurations and low Reynolds numbers (at least two orders of magnitude lower than full scale conditions). Recently, DNS of a zero pressure gradient boundary layer performed at $Re_\vartheta = 6600$ were presented (Sillero, 2013), where wall pressure fluctuations are analysed and compared with experimental data. Higher Reynolds number flows (Re_τ=1440) were performed in DNS simulation by Hu et al. (2006), where point spectra are reported. More complex geometries were investigated by Kim and Sung (2006), who analysed WPF and flow-induced noise from a turbulent boundary layer over a bump, for a flow with a low Reynolds number (Re_ϑ=300).

On the contrary, large eddy simulations (LES) are not limited to low Reynolds number, since only the large energetic scales are directly simulated. Recently, in Park and Moin (2014) WPF were computed by LES with wall functions in a channel flow at $Re_\tau = 2000$. The reported results showed that, although wall pressure fluctuations spectra and their space-time characteristics agree with DNS data, improvements are required for the high frequency range.

A different numerical approaches for the evaluation of WPF is based on Reynolds-Averaged Navier-Stokes (RANS) simulation coupled with statistical models for the pressure spectrum. With this approach, in 2005 Lee et al. (2005) predicted the frequency spectrum of wall pressure fluctuations; the autospectrum of the vertical component u_2 of the fluctuating velocity was modelled by the Chase formulation (Chase, 1980). The predicted pressure spectra mirror experimental data only for equilibrium flow, while WPF were under-predicted in the non-equilibrium conditions. RANS simulation of free surface flows was applied in Lee et al. (2005) to characterize wall pressure spectra acting along the hull of a realistic ship, but no comparison with experimental data is shown. Similarly, Peltier and Hambric (2007) proposed a stochastic model to predict WPF spectra using data from RANS solution, in mild favourable, zero and mild adverse pressure gradient conditions, for values of Reynolds number (based on momentum thickness) between 1440 and 9000. The agreement with experimental data is generally good, although the model fails for strong favourable pressure gradient, where the results deviate from experimental data.

On the other hand, few data (Magionesi et al., 2012) are available at full scale, because measurements are difficult and expensive. In this context, WPF modelling exploits a combination of analytical, numerical and experimental techniques, aimed at identifying scaling laws for pressure spectra and spatial evolution in the physical domain or in the wavenumber-frequency domain from laboratory experiments.

Most of the literature about WPF modelling is devoted to the study of equilibrium turbulent boundary layers on flat plates in zero pressure gradient (ZPG) flow, for which WPF scale rather well with a combination of inner flow parameters at high frequency and outer flow parameters in the low frequency range (Farabee and Casarella, 1991; Ciappi and Magionesi, 2005; Bull, 1996; Goody, 2004; Keith et al., 1992). Moreover, in the mid frequency range there exists an overlapping region where data collapse using both scaling laws; in this range, they depend on ω^{-1} and on Reynolds number, as shown in Bradshaw (1967).

In addition to local models, a number of semi-empirical models for spatial characterization of wall pressure spectra under zero pressure gradient TBL were proposed (Corcos, 1963a, 1963b; Efimtsov, 1981; Chase, 1980). These models can be divided into two groups: in the first, they postulate that space-time characteristics of WPF can be split into two independent contributions from streamwise and spanwise separations; in the second group, instead, these two contributions are coupled. To the former group belongs the Corcos model, who proposed a spatial cross-spectrum (space-frequency) model dominated by the convective terms. It was shown that the Corcos model overestimates the response in the subconvective region (Ciappi et al., 2009), which is the region of major concern in marine applications, due to the low velocity of the flow and the typical massive characteristics of the marine and submarine structures. To the second group belongs the Chase model (Chase, 1980), which extends the previous model to the low wavenumber range.

These existing models for cross spectral density of the fluctuating pressure are based on data fitting under ideal conditions and can fail when applied to real structures. Some attempts to include the effect of pressure gradient and curvature in the Corcos model are presented in the technical literature (Schloemer, 1966), while to the authors' knowledge, no attempt to tune the Chase parameter for a complex boundary layer can be found.

In general, the presence of pressure gradients, curvatures and free surface implies a re-analysis of scaling parameters and spatial correlation. Previous works addressed the effects of curvature and pressure gradients with special experimental set-up, designed to highlight the different contributions separately. The previous investigations showed that an overall effect of adverse pressure gradients onto the wall pressure field statistics is an increase of the wall pressure fluctuations in the low- and mid- frequency ranges, whereas little effect was observed in the high-frequency range; furthermore a reduction of the convection velocity ratio U_c/U_e, where U_c represents the velocity at which the turbulent eddies are convected and U_e is the external velocity, has been already pointed out (Schloemer, 1966). On the other hand in the high frequency region different behaviours were identified for the favourable pressure gradient: in Schloemer (1966) a sharp decrease of pressure spectra levels is experimentally obtained, while in Peltier and Hambric (2007) the authors highlight a common high frequency behaviour under inner-variable scaling for zero pressure gradient (ZPG), adverse pressure gradient (APG) and favourable pressure gradient (FPG). The motivation of this discrepancy of data at high frequency could be related to transducer resolution problems.