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Discrimination of acoustic and turbulent components from aeroacoustic wall pressure field

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ABSTRACT

The investigation of the wall pressure excitations over transportation vehicle panel is of great interest to improve the knowledge of vehicle interior noise transmission and also for future noise reduction strategies. A particularly useful task concerns the characterization and the separation of both acoustic and turbulent components of the wall pressure excitation. A new application of the Proper Orthogonal Decomposition (POD) is tested from two different databases: (i) wall pressure fields synthesized from theoretical average models and (ii) wall pressure fields obtained from Lattice Boltzmann Method numerical simulation. In each case, POD application leads to an energetic partitioning of the wall pressure field that permits to well decouple both acoustic and turbulent fields, especially for mid and high frequencies under interest. To validate such separation and to demonstrate the effectiveness of the POD method, the wavenumber spectrum analysis as well as phase analysis is successively performed. Such a new splitting method provides an instantaneous acoustic–turbulent separation of an inhomogeneous wall pressure field, suggesting many useful future applications.

1. Introduction

In transportation vehicles (automotive, aircraft, train), the acoustic comfort of driver and passenger is becoming prioritarily important. For car manufacturers, this is reinforced with the new generation of electric cars and their silent engines. In the automobile context, at high velocities, the aerodynamic source has a dominant contribution to the vehicle's interior noise and the side window is one of the relevant acoustic transmission paths. To reduce the interior noise, the study of panel vibrations is then of great interest and requires enhancing the learning about excitation and transmission mechanisms. More particularly, the identification and the characterization of exterior wall pressure field is essential to better predict its transmission in the vehicle interior allowing an implementation of future noise reduction strategies.

In fact, the car window vibrates under the influence of the aerodynamic exterior flow. It is now well known that such an exterior instantaneous wall pressure field inducing panel load is composed of a turbulent component and an acoustic component [1–4] and these two excitation fields contribute to the interior noise. The complex turbulent contribution is related to the Turbulent Boundary Layer (TBL) flow developing over the car window. This TBL flow is also subjected to be

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affected by the A-pillar vortex and the door mirror wake. The acoustic component arises from acoustic waves generated in the exterior turbulent flow. Both components have been identified, especially in the wavenumber frequency domain (see Section 2). Previous analyses have shown that the acoustic excitation field seems dominant in noise transmission inside the car [1,5,3]. However to improve the knowledge of vehicle interior noise transmission, it is important to characterize separately both acoustic and turbulent components of the wall pressure excitation and not only in the spectral domain.

The aim of this work is then to propose a new way for discriminating instantaneously both acoustic and turbulent contributions of the wall pressure field. In fact, wall pressure field excitation over a car window is fully of multiscale nature. Such a characteristic is encountered in many physical and mechanical problems like in turbulent flow where different scale vortices are present. In this last case, the analysis and extraction of vortex dynamics is then of great importance to understand the turbulence production/dissipation mechanisms and its general properties. Thus, a lot of different methods have been previously implemented to extract large and small scale vortices from spatio-temporal database. Some applications of many filtering methods were presented in Adrian et al. [6]. Note that applications of these methods highly depend on the nature of the available database and on the chosen definition of the vortex. Furthermore, as a function of the choice of the vortex extraction criteria (time or space scale, core, energy, etc.) very different methods (scale decomposition, homogeneous and inhomogeneous filtering, Eulerian or Lagrangian point of view, etc.) can be implemented to discriminate the selected vortex from instantaneous pictures as well as from a statistical point of view. Another typical example that is mainly related to the present work concerns aeroacoustics. Indeed, in such a case, acoustic variables and turbulent ones are simultaneously present in the turbulent compressible flow. They are associated with very different time and space length scales and also with different energy repartitions. Moreover, these time-dependent variables interact with each other and it is quite difficult to discriminate these variables. Then by analogy with the above examples, before implementing a mathematical tool allowing the decoupling of acoustic and turbulent variables of the wall pressure, one has to state about the differences between both contributions (spectral or physical content, energy content, etc.).

In the following, we are going to successively focus on these points. The next part first recalls the main properties of aeroacoustic wall pressure field. Second, methods previously considered for separating these two contributions are presented. Third, POD technique is detailed with an emphasis of its interest in such an application. Section 3 proposes a first splitting application based on numerical synthesized aeroacoustic pressure field defined, thanks to the prescription of the statistical properties of the turbulent and acoustic components. Then based on a numerical simulation of the flow around a realistic model car, more realistic wall pressure fields are extracted and used to test the robustness of the POD splitting technique (Section 4).

2. Filtering wall pressure field

In this part, one assumes a wall pressure field, $p(\mathbf{X},t)$, available (theoretically, experimentally or numerically) for a certain time duration (N_t time steps) on a two-dimensional surface plate, S_{plate}, having a mesh grid discretization of $M=N_x\times N_y$ points. $\mathbf{X}=(x,y)$ indicates the two-dimensional vector space variable. Direction Ox is supposed to be the main flow direction.

Assuming a statistically stationary wall pressure field, one firstly splits the pressure field into a mean and a fluctuating part, thanks to the Reynolds decomposition: $p(\mathbf{X},t)=\overline{p}(\mathbf{X})+p'(\mathbf{X},t)$, where an overbar indicates the time average. Then, we focus on the fluctuating part which considers both acoustic and turbulent fluctuations. The objective is to express $p'(\mathbf{X},t)$ as follows:

$$p'(\mathbf{X},t)=p_{\text{acou}}(\mathbf{X},t)+p_{\text{turb}}(\mathbf{X},t) \tag{1}$$

where p_{acou} and p_{turb} are the acoustic and turbulent fluctuations respectively. It should be noted that in following figures, the notation p_{aeroacou} will be refer to the fluctuating aeroacoustic field, $p'(\mathbf{X},t)$.

2.1. *Wall pressure field properties*

Based on previous investigations [7], the acoustic waves are several orders of energy magnitude smaller than the turbulent pressure field. Then turbulent wall pressure loading is more energetic than acoustic loading. In a dB scale, that corresponds to a difference of an order of 10–20 dB. Furthermore, the acoustic part of the wall pressure field propagates at the sound speed c_0 in the medium. Conversely, turbulent part convects at the local flow speed U_c which is smaller than the exterior mean flow field U_∞ due to the presence of the boundary layer flow. Accordingly, the correlation lengths associated with both contributions differ. The wavelengths of the acoustic part are then greater than the ones related to the turbulent part [1,8]. This is always true apart from very small frequencies.

2.2. *Splitting of wall pressure field*

From the above considerations, several attempts have been previously made to discern these two parts. To the authors' knowledge, previous past flow splitting procedures were mainly based on Wavenumber Frequency Spectrum (WFS) analysis. In the previous experimental works, the WPS is accessed from the multipoint space–time correlations