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On wall pressure fluctuations and their coupling with vortex dynamics in a separated–reattached turbulent flow over a blunt flat plate

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ABSTRACT

This study deals with the numerical predictions through Large-Eddy Simulation (*LES*) of the separated–reattached turbulent flow over a blunt flat plate for analyzing main coherent structure features and their relation to the unsteady pressure field. A compressible approach that inherently includes acoustic propagation is here followed to describe the relationship between pressure fluctuations and vortex dynamics around the separation bubble. The objective of the present work is then to contribute to a better understanding of the coupling between the vortex dynamics and the wall pressure fluctuations. The filtered compressible Navier–Stokes equations are then solved with a numerical method that follows a Lax–Wendroff approach to recover a high accuracy in both time and space. For validations, the present numerical results are compared to experimental measurements, coming from both the Pprime laboratory (Sicot el al., 2012) and the literature (Cherry et al., 1984; Kiya and Sasaki, 1985; Tafti and Vanka,1991; Sicot et al., 2012). Our numerical results very well predict mean and fluctuating pressure and velocity fields. Flapping, shedding as well as Kelvin–Helmholtz characteristic frequencies educed by present simulations are in very good agreement with the experimental values generally admitted. These characteristic modes are also visible on unsteady pressure signatures even far away from the separation. Spectral, POD and EPOD (extended POD) analyses are then applied to these numerical data to enhance the salient features of the pressure and velocity fields, especially the unsteady wall pressure in connection with either the vortex shedding or the low frequency shear-layer flapping. A contribution to the understanding of the coupling between wall pressure fluctuations and eddy vortices is finally proposed.

1. Introduction

Massively separated flows have engineering concerns since they occur in many aerodynamic applications, such as around ground vehicles, train or aircraft bodies. Such flow configurations are highly 3D and mainly unsteady with however well-known characteristic frequencies. One of fundamental issues relates to the mechanisms driving the acoustic propagation in the far field surrounding these aerodynamic bodies. Another one is the sound propagation toward the interior of the vehicle since main sound frequencies occur on the same range as the voice frequencies. If one wants to control acoustic disturbances and develop noise reduction process applied to a quiet vehicle, it is first essential to better understand the mechanisms involved in the noise generation and its transmission toward the habitacle. Sources of noise are essentially due to the coupling between eddy structures and the unsteady pressure field in the core of the flow (Hoarau et al., 2006). A major challenge is therefore to accurately predict the pressure fluctuations generated within the flow that is central to the acoustic source generation along the solid surfaces. This study is hence devoted to a better understanding of the production of fluctuating pressures on a solid wall on which a massively separated flow impinges. We here deal with the numerical simulation of the turbulent flow generated around a blunt flat plate with a sharp leading edge. This configuration constitutes an academic model for studying the main features of massively separated-reattached turbulent flows, encountered for instance around vehicles, mainly in the vicinity of the front hood or close to the window or door post of a car.

In the past, this configuration has widely been studied experimentally. Numerous experimental results are available in the literature on the structure of turbulent flow separation bubbles and its relaxation after the reattachment (Castro and Epik, 1998; Castro and Haque, 1987; Cherry et al., 1984; Eaton and Johnston, 1981; Hoarau et al., 2006; Kiya and Sasaki, 1983; 1985; Sicot et al., 2012). The dynamics of the separation bubble and its reattachment have

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mainly been reviewed on both the flow along a side of a blunt flat plate and the backward-facing step flow field. The structure of large scale vortices have been studied by Hillier and Cherry (1981); Kiya and Sasaki (1983, 1985) and Cherry et al. (1984) that educe the main mechanisms involved in the separation bubble dynamics. They showed that the flow in the separation bubble is governed by two main mechanisms: the *shedding* of large-scale vortices downstream of the separation and a low-frequency unsteadiness called *flapping*, linked to the shredding and enlargement of the bubble. The role of the shear layer edging the separation in the bubble dynamics and the reattachment was also demonstrated (Castro and Epik, 1998; Castro and Haque, 1987). The connection between these main mechanisms is still not clear and deserves more results for further analysis. The three-dimensional feature of large-scale structures in the reattaching zone was underlined and its influence on the wall pressure fluctuations was studied through either cross-correlations (Kiya and Sasaki, 1983; Saathoff and Melbourne, 1997) or extended POD analysis (Hoarau et al., 2006; Sicot et al., 2012; Tran, 2012). Wall pressure fluctuations are related to the motion of large-scale vortices, especially hairpin vortices in the reattachment region that produce large amplitude fluctuations. The influence of the free-stream turbulence on the flow dynamics have also been reviewed (Castro and Epik, 1998; Saathoff and Melbourne, 1997) and an increase of turbulence intensity tends to reduce the reattachment length. Although the mean pressure was decreased at separation, the magnitude of the pressure fluctuations in the separation bubble is increased (Saathoff and Melbourne, 1997). It was however shown that “the spanwise length of vortices in the separation bubble is not directly related to longitudinal velocity fluctuations in the free-stream” (Saathoff and Melbourne, 1997). Experimental analysis also investigated the relaxation occurring downstream the reattachment. Although some characteristics (log-law for instance) of canonical boundary layers are re-established rather rapidly, the energetic *mixing-layer like* structures occurring around reattachment evolve very slowly since 70 boundary layer thicknesses are needed to recover common structures of a standard boundary layer (Castro and Epik, 1996; 1998; Sicot et al., 2012). Following these results, authors (Castro and Epik, 1996; 1998) conjectured that second order Reynolds stress models are not able to predict the slow decay of the energetic large scale structures in the outer part of the flow and its influence on the inner region. We can then think that *DNS* and resolved *LES* remain ideal tools to mimic such flow phenomena.

Unlike numerous experiments, only few numerical simulations of the flow generated around a blunt flat plate exist in the literature. Most of these computations concern low to moderate Reynolds number configurations aiming at studying steady laminar flow to unsteady regime with quasi-periodic vortices shed in the vicinity of the reattachment (Lamballais et al., 2010; Tafti and Vanka, 1991). Authors studied the curvature effects of a rounded leading edge on the dynamics of the separation (Lamballais et al., 2010). Large-Eddy Simulations have also been conducted to investigate the transitional separated-reattached flow over a flat plate (Yang and Abdalla, 2009; Yang and Voke, 2000; 2001). As far as we can note in these previous results for low and moderate Reynolds number regimes, the reattachment length seems very sensitive to the Reynolds number. Even at high Reynolds number regime, the reattachment length (L_R) does not recover a unique value since it is distributed in between [4, 5.5] (See Cherry et al., 1984 for more details). To try to explain this wide-ranging of L_R values, the influence of free-stream turbulence and surface curvature change have been reviewed on the transition process from laminar separation to reattachment in a turbulent boundary layer. At present, reasons of this broadness (Bruno et al., 2014) are still unexplained and no specific value of this length emerges from previous result, meaning that new numerical results must be provided to get a better insight into this configuration. Nevertheless, several authors discussed the existence of vortex shedding and low frequency shear-layer flapping (Yang and Voke, 2001). Although the connection between these two main mechanisms is not completely elucidated, they postulated that two different topological structures could be associated with the normal shedding and the shedding responsible for low-frequency flapping. Another connection that needs to be elucidated is the relationship between the vortex structure dynamics and the pressure fluctuations. Ji and Wang (2010) studied the aeroacoustics of turbulent boundary layer flows over backward and forward facing small steps. By using incompressible *LES* coupled with the solution of a Green’s function following Lighthill’s analogy, they analyzed frequency spectra of wall pressure to contribute to a better understanding of noise production. However, all these studies essentially concern incompressible flow simulations and to obtain a better description of the relationship between pressure fluctuations and vortex dynamics for separated-reattached flow over a flat plate, a compressible approach might be more suitable since acoustic propagation inherently included. This study is thus devoted to the numerical predictions through compressible Large-Eddy Simulation (*LES*) of the separated–reattached turbulent flow over a blunt flat plate with a right-angled leading edge. To our knowledge, there does not exist any study of compressible flow over the turbulent flow over a forward facing step which provides an analysis of the main coherent structure features and their relation to the unsteady pressure field. Hence, the objective of this work is two fold: *(i)* to provide a well resolved *LES* reference databasis for analyzing the dynamics of the main coherent structures in the separated–reattached turbulent flow over a blunt flat plate, and *(ii)* to contribute to a better understanding of the coupling between the vortex dynamics and the wall pressure fluctuations, especially in connection with either the vortex shedding or the low frequency shear-layer flapping.

In this work, we solve the filtered compressible Navier–Stokes equations following a *LES* approach with a dynamic vorticity model to account for subgrid scales. The governing *LES* equations and the subgrid-scale modeling are presented in Section 1. Following a Lax–Wendroff approach, the numerical method employs a 7th-order scheme introduced in Daru and Tenaud (2004, 2009), named OS7, which recovers a high accuracy in both time and space with a great efficiency in terms of CPU time compared to more conventional schemes. Numerical approximations are described in Section 2 and the numerical ingredients, including the definition of the computational domain, boundary conditions, and grid generation, are presented in Section 3. In Section 4, we then validate our numerical results by comparisons with experimental measurements, coming from both the Pprime laboratory and different experiments (Cherry et al., 1984; Kiya and Sasaki, 1985; Sicot et al., 2012; Tafti and Vanka, 1991). Thus, spectral, POD and EPOD (extended POD) analyses are applied on the present numerical data to determine the salient features of the pressure and velocity fields. A contribution to the understanding of the coupling between wall pressure fluctuations and eddy vortices is eventually proposed. Finally in Section 6, we conclude and present prospects for future work.

2. The governing LES equations and the subgrid-scale modeling

The governing equations are the compressible Navier–Stokes equations filtered with an implicit spatial filter (noted $\overline{(.)}$) combined with the density-weighted Favre decomposition (Favre, 1965) $\widetilde{(.)}$. The characteristic filter size depends both on the local mesh size and on the intrinsic dissipation of the numerical scheme. This suggests to use schemes for *LES* that exhibit as low dissipation error as possible because the greater the intrinsic dissipation, the larger the size of the implicit filter.

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