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Wall pressure and conditional flow structures downstream of a reattaching flow region

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ABSTRACT

The separating and reattaching flow over a thick plate with sharp angle at *Re* = 80,000 is investigated using pressure and HS-PIV measurements. After having studied the mean flow properties, which are found in good agreement with the literature, a particular emphasis is given concerning the eduction and the analysis of the evolution of the large scale vortices downstream of the reattachment. This is done using an adapted multi-time and multichannel stochastic estimation of the velocity correlated with the fluctuating wall pressure. Swirling strength and Finite Time Lyapunov Exponents are then used in order to detect and characterize the structures and their dynamics. Conditional statistics based on the feature longitudinal position are computed in order to educe intensity, size, position and convection velocity of each conditional feature. A rapid longitudinal decrease of the fluctuating kinetic energy carried by these conditional structures has been observed, highlighting their rapid loss of coherence downstream mean reattachment.

1. Introduction

Understanding the intrinsic spatial and unsteady features of separating and reattaching flows has a great importance for the design and control of a large number of engineering applications. In particular, unsteady flow structures have to be educed and tracked in the flow. Even in turbulent flows, it is believed here that extension of topology based analysis, coupling for instance the detection of vortices with associated moving saddle point (Haller, 2001) permits such analysis. As part of a French ANR project (DIB: Dynamic, Unsteadiness, Noise), the present study investigates the turbulent flow generated by a blunt flat plate with right-angled corners at Reynolds number 80,000. Two dimensional separation–reattachment flow, occurring from a sharp corner, have been a subject of many studies (e.g. Bradshaw and Wong, 1972; Kiya and Sasaki, 1985; Cherry et al., 1984; Hudy et al., 2007). Measurements of second order moments, integral timescale, power spectrum or cross correlation between the wall pressure and velocity fluctuations were obtained and analyzed by these authors. Kiya and Sasaki (1985) used one-point velocity pressure correlation to extract coherent vortices in the reattaching region and proposed a description of the large scale vortices and the unsteady reverse flow properties in this region. In their study, conditional averaging was performed with respect to the extrema of the wall pressure trace located at one point close to the mean reattachment. A large scale vortex was found to be associated with a pressure minimum and a pressure maximum was found to occur between the passage of two successive vortices, on average. This averaged picture of the shed vortices was completed with convection velocities and scales deduced from statistical quantities like correlation and spectra of velocity and wall pressure. Kiya and Sasaki (1985) conjectured that large scale vortices in the reattaching zone have a hairpin shape and that hairpin vortices are universal to nominally two-dimensional separation bubbles. These large scale vortices shed from the shear layer are then advected downstream of the mean reattachment point and dissipated into the outer boundary layer, as schematically described in Fig. 1. Numerical simulations have also been performed at lower Reynolds number (e.g. Abdalla and Yang, 2004) and have demonstrated the three-dimensionality of the flow, particularly downstream of the reattachment.

The objective in this paper is twofold: to analyze the relationship between the shed structures and the wall fluctuating pressure, and to characterize their evolution downstream of the reattachment, in terms of scales, convection velocity and kinetic energy content, not only using classical statistical tools, but using the information available from the structures themselves. To this aim, simultaneous High Speed PIV (HS-PIV) and wall pressure measurements have been carried out in the reattachment region. After having studied the mean flow properties, the fluctuating velocity correlated with the wall pressure is estimated using an adaptation

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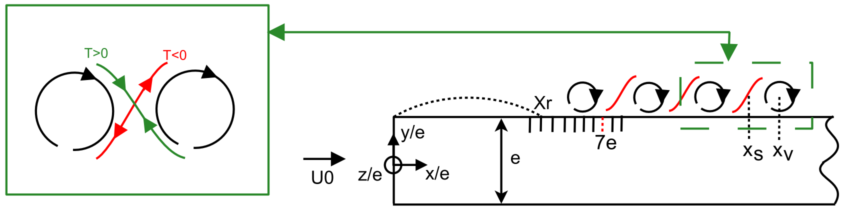

Fig. 1. Schematic of the flow configuration and the ridge line of the FTLE field. The longitudinal positions of the pressure sensors in the mid-span plane are indicated by a black line. The red dashed line indicates the longitudinal position of the pressure sensors located in a transverse line. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of stochastic estimation, and the coherent structures are analyzed using both Eulerian and Lagrangian criteria.

The first section presents the experiment and the post-processing tools that have been developed. Following sections deal with the analysis of the mean motion, the eduction of the coherent vortices, and the evolution of these large scale vortices downstream of the mean reattachment.

2. Experimental set-up and post-processing

The experiments are performed in a low-speed Eiffel type's wind tunnel. The square nozzle section has dimensions of 460 mm × 460 mm. The blunt flat plate is e = 30 mm thick, 1300 mm long and 460 mm wide giving a solid blockage of 6.5% and an aspect ratio of 15.3. The plate is parallel to the nominally smooth stream (Fig. 1).

The leading edge is located 300 mm downstream the jet outlet. The trailing edge is streamlined to minimize any wake-induced unsteadiness. The experiments are performed at a free-stream velocity U_0 = 40 m s^{-1} ($Re = 8 \times 10^4$ based on the thickness of the plate). The flow will be described henceforth using a cartesian co-ordinate system (x,y) to indicate the axial and vertical directions. The origin is set on the leading edge of the plate at the mean stagnation point. The corresponding velocity components are denoted by U and V. In the next sections, all the quantities are made non-dimensional using U_0 and e.

2.1. Measurements

2.1.1. HS-PIV

HS-PIV systems have been used to record images of particles, provided by an oil generator, having a mean diameter of 1 μm. Illumination is provided by a New Wave PEGASUS Laser emitting two pulses of 10 mJ (laser sheet thickness ⩽1 mm). About 16,000 velocity fields were acquired with a PHOTRON ABX-RS camera in the symmetry plane y = 0 at a frequency rate of 2 kHz in order to obtain a long time interval of high speed PIV data. The resolution of the sensor is 1024 × 1024 pixels^2 with a pixel size of 0.108 mm/pixel. The time interval separating the two laser shots (20 μs) was optimized to reduce out of cell and out of plane errors while keeping the dynamic range for velocity measurements as large as possible. A multipass algorithm with a final interrogation window size of 16 × 16 pixels^2 and 50% overlapping is applied. Spurious velocities are identified and replaced using both signal-to-noise ratio and median filters. The maximum uncertainty on instantaneous velocity measurements are estimated at 0.54 m/s (displacement of 0.1 pixel). The HS-PIV domain is located from $x/e \simeq 3$ to $x/e \simeq 10$. Other low frequency PIV planes upstream of the reattachment location have been acquired to complement the mean flow analysis.

2.1.2. Fluctuating pressure measurement

Measurements of the fluctuating wall pressure have been obtained with ten *sensortechnics* off-set differential pressure sensors located in the mid-span plane from x/e = 5.25 to 8.6 downstream of the reattachment (see Fig. 1). Sensors were also mounted on a transverse line (x/e = 7) at intervals of 0.3e from $z/e = -2$ to z/e = 2. Off-set sensors have the advantage to increase the pressure range of sensors because the fluctuating pressure decreases along the flexible tube between the pressure tap and the sensor. Those sensors, are differential with a bandwidth of [0 Hz to 1.6 kHz] and a pressure range of 250 Pa. Details of the methodology are provided in Ruiz et al. (2010). The maximal error on fluctuating pressure is evaluated at 9.4 Pa. The sampling frequency is 5.12 kHz and a cut-off frequency of the anti-aliasing filters is set at 2 kHz. A square signal triggered by the Q-switch of the first laser cavity is used for the synchronization of PIV and pressure acquisition. The Q-switch signal of the first laser cavity is used to trigger a square signal of duration 250 μs. This square signal is acquired simultaneously to the pressure signals at the acquisition frequency of the signal recorder (Δte = 195 μs). We are therefore sure that each PIV measurement is detected on the recorded signal. The maximum error between the PIV shot and the time detection is therefore (Δte = 195 μs).

2.2. Post-processing techniques

2.2.1. Stochastic estimation of the velocity field from the pressure data

As will be seen in the following section and in agreement with the literature, a strong spatio-temporal coherence is found in a frequency range around $\frac{fe}{U_0} \simeq 0.12$, both in the velocity and in the pressure data (the frequency is non dimensionalised using the plate thickness e and the upstream velocity U_0). This coherence is to be related to the large scale vortices emanating from the separated shear layer and dissipating once embedded in the outer layer downstream of the reattachment. In order to analyze the spatio-temporal characteristics of these structures and their evolution, a multichannel and multi-time version of stochastic estimation of the fluctuating velocity conditioned to the pressure traces has been developed. For comparison, classical LSE (Linear Stochastic estimation) has also been carried out. The classical LSE consists in finding the best approximation of the conditional velocity given p at the sensors location under the form $\tilde{u}_i(X,t) = B_{ij}(X)p_j(t)$ where p_j denotes the pressure at sensor j. Here the ten sensors located in the mid-span plane, as described above, are used for the estimation. The coefficients $B_{ij}(X)$ are classically determined by solving the linear system $\overline{u_i(X,t)p_k(t)} = B_{ij}(X)\overline{p_j(t)p_k(t)}$ (Adrian, 1979). Two modifications are made to enhance the estimation: First, the pressures of the ten sensors are considered in a time window centered around the instant of the estimation. Second, a POD is performed on this spatio-temporal pressure data set (this technique is actually well-known as MultiChannel Singular Spectrum Analysis in the meteorology field (Broomhead and King, 1986). The modes are then extended following the Extended POD procedure introduced by Borée (2003) to estimate the velocity fluctuations correlated with the pressure. This consists in taking the N first POD coefficients as the conditioning events in LSE. If all modes are considered, a multi-time LSE is recovered. This spatio-temporal