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Control of the coherent structure dynamics downstream of a backward facing step by DBD plasma actuator

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ABSTRACT

A non-thermal surface plasma discharge (dielectric barrier discharge) is installed at the step corner of a backward-facing step ($U_0 = 15$ m/s, $\mathrm{Re}_h = 30{,}000$, $\mathrm{Re}_\theta = 1650$). Wall pressure sensors are used to estimate the reattaching location downstream of the step and also to measure the global wall pressure fluctuation coefficients. A parametric study is performed where the voltage amplitude, the burst frequency and the duty-cycle of the input high voltage are investigated separately regarding their performance. Mean and phase-averaged velocity fields are obtained by time-resolved PIV and they are used to analyze the impact on the dynamic of the flow. The minimum reattaching position is achieved by forcing the flow at the shear layer mode through 2D periodic perturbations in the initial region at $\mathrm{St}_h = 0.25$ ($\mathrm{St}_\theta = 0.013$), where a large spreading rate is obtained by increasing the organization and periodicity of the vortex street. A mean recirculation reduction by 22% is observed. Pressure fluctuations are maximized for an actuation at half the shear layer mode ($\mathrm{St}_h = 0.125$ or $\mathrm{St}_\theta = 0.006$). For this subharmonic forcing mode by single-frequency perturbation, the vortex pairing is enhanced. The present study shows that the subharmonic mode corresponds to the well-known shedding mode that promotes flow structures remaining coherent over a long distance and dominating all the flow dynamics, this including the dynamics of the reattaching point.

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1. Introduction

Studies investigating the use of mechanical, fluidic or plasma actuators for flow control, as well as the number of funded projects on the topic, are increasing over the years. Nonetheless, flow control technologies are still not used by aeronautical, and more generally transport, industry because of the technology, implementation and safety maturities are considered as being too low for the moment. However, some recent implementation of active flow control on real aircraft such as the ecoDemonstrator from Boeing and the SFWA demonstrator from Airbus gives further motivation to academic for researches focusing on turbulent flow manipulation by active flow control actuators. Regarding plasma actuators, one of the interests of this type of active system is its intrinsic principle of electro-mechanical conversion that implies fast momentum transfers. By adjusting the electrical parameters of the electrical signal applied to the air-exposed electrode, the amplitude, frequency and duty-cycle of the periodic flow fluctuations produced by the actuator can be easily tuned (see Corke et al., 2010; or Benard and Moreau, 2014).

The present investigation concerns the manipulation of a turbulent flow separation downstream of a backward-facing step (BFS) by a surface plasma discharge. This simple geometry leads to a typical separated shear layer affected by the highly unsteady reattaching flow. Depending on the underlying physics, different Strouhal numbers (St) can be defined. A primary periodic organization arrives from the separated shear layer developing from the separation point. This separated shear layer evolves as a typical mixing layer in its earlier stage of formation with a typical 'shear layer mode' of instability at about $\mathrm{St}_\theta = 0.012$ (where θ is the momentum thickness of the boundary layer at the trailing edge and the freestream flow U_0 is considered) (Hasan, 1992; Chun and Sung, 1996). This implies the development of vortical flow structures after a roll-up of the separated boundary layer, organized in a periodic manner, which entrains irrotational fluid from the non-turbulent regions bounding the shear layer. Initially formed at high frequency, the vortices can pair reducing the frequency signature of the vortical flow structure with the downstream position. The impact on the bottom wall of these coherent flow structures is thus a periodic phenomenon usually referred as vortex shedding

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mode of the BFS flow (a typical value of about $St_{Xr}=0.6$ is reported in Cherry et al., (1984); Driver et al., (1987); Hudy et al., (2003) among many others, with X_r the position of the mean reattaching flow). The reattachment location is highly unsteady partially due to the periodic impact of the vortical flow structures. Nonetheless, as it is reported in Lee and Sung (2001) or Kya and Sasaki (1985), a flapping motion of the shear layer also contributes to the widening of the separated shear layer. This flapping mode is a low frequency phenomenon with a frequency signature at about $St_h \sim 0.02$ (where h is the height of the step) that contributes to the periodic displacement of the reattachment point. The BFS configuration is then a rich environment in terms of periodic motions and therefore it offers a lot of flow control scenarios

The present study is an experimental parametric investigation regarding the capability of plasma discharge (Moreau, 2007; Corke et al., 2010; Wang et al., 2013, Benard and Moreau, 2014) for manipulating a turbulent separated flow with an unsteady reattachment. The effectiveness of the actuation is evaluated by two metrics. The primary one is the mean flow reattachment location X_R, a traditional metric for studies related to BFS flows. The second metric is more original as it concerns a global measurement of the wall pressure fluctuations. The mean flow reattachment is identified by using a series of unsteady pressure sensors installed on the bottom wall of the BFS model. Theses sensors are also used for computing the spatial integral of the wall pressure fluctuation coefficients, defining a global estimator of the fluctuations in the flow. The voltage amplitude, the burst frequency and the duty-cycle of the electrical signal applied to a linear dielectric barrier discharge are the independent variables of the optimization problem. In a second part, following the results of the parametric investigations, time-resolved flow measurements are presented. Phase-averaged flow fields are also investigated in order to reveal the influence of a DBD plasma actuator when powered in a manner that optimizes its influence on the mean flow and the vortex flow organization and dynamics.

2. Experimental setup

The backward-facing step model has a height, h, of 30 mm and a spanwise length of 300 mm. This model is installed in a closed-loop wind-tunnel having a moderate turbulent intensity (~0.8%). The dimension of the test section is $300 \times 300 \times 1000$ mm^3. All measurements are performed for a free-stream velocity, U_0, of 15.6 m/s. This results in a Reynolds number (based on h) of 30,000. A glued zig-zag tripper (thickness of 300 µm) is installed 10 h upstream of the step corner in order to guarantee a fully turbulent boundary layer at the separation point and results which are not strongly influenced by the inlet condition. At the step corner, the momentum thickness is 1.65 mm ($Re_\theta = 1650$), the shape factor is about 1.6 and the boundary layer thickness δ is equal to 11 mm (measured by LDV in a preliminary campaign see Sujar-Garrido et al., 2015).

The step model is made of a 3-mm thick machined PMMA piece. The electrode arrangement is introduced in Fig. 1. The air-exposed and the grounded electrode have a width of 15 and 10 mm respectively and the gap between them is fixed at 2 mm. By construction (the model is used as dielectric barrier), the actuator protuberance into the flow is limited to the electrode thickness (i.e. 60 µm). The actuator covers 80% of the span of the test section. Its geometry has been designed for producing a thin wall jet oriented from the air-exposed electrode to the grounded one. This geometry has been selected accordingly to the parametric study proposed in Sujar-Garrido et al. (2015) where this position was identified as the most effective one (among 5 different locations) for minimizing the recirculating bubble. In burst modulation operation mode (see Fig. 1), the peak flow velocity of the produced wall jet does not exceed 4 m.s^{-1} in average. At 20 kV voltage amplitude and $f_{AC} = 2000$ Hz, the electrical consumption of this actuator operating in burst modulation is of about 20 W.

The high voltage power has a maximum output voltage of +/− 30 kV and a maximum AC peak current of +/−40 mA (Trek 30/40). The waveform sent to the power amplifier is produced by a signal generator card (NI, PXI-5402). In the present investigation, the electrical parameters of interest are the voltage amplitude, the burst frequency f_{BM} and the duty-cycle. A low frequency gate function is used to trigger the ac sine voltage ($f_{AC} = 2$ kHz) for producing a burst modulation. This gate function allows the plasma discharge to be alternatively turned off and on at frequencies in the range of the periodic fluctuations of the natural flow (Benard and Moreau, 2010). One can notice that the ac frequency has been doubled compared to our precedent investigation in Sujar-Garrido et al. (2015).

The bottom wall downstream of the step is equipped with 55 pressure taps distributed along the streamwise direction, from $x/h = 1$ to $x/h = 9$ located at mid-span. The distance between two successive taps is 4.5 mm, resulting in a spatial resolution of 0.15 h. A set of 32 unsteady pressure sensors (bandwidth of 2 kHz for full scale pressure of 250 Pa) are used to compute the streamwise distribution of the rms pressure fluctuations normalized by the incoming flow dynamic pressure. Then, the wall pressure fluctuations are presented in coefficient form:

$$C_{P'} = \frac{\sqrt{\frac{1}{n}[(P_1 - P_0) + (P_2 - P_0) + \ldots + (P_n - P_0)]}}{0.5\rho U_0^2} \quad (1)$$

where P_0 and U_0 refers to the reference values of the static pressure and streamwise freestream velocity, respectively. In all the pressure measurements, the pressure signals have been sampled at 1000 Hz and 5000 data samples are recorded. For the Power Spectral Density (PSD) of the wall pressure signals, the acquisition sequence is reproduced 20 times in order to finally obtain averaged spectra. The location of the mean reattachment point is one of the metric used in this study to evaluate the effectiveness of the control. Here, this location, X_R, is estimated by the position of the $C_{P'}$ peak along the stream wise direction on the wall (Fig. 2) as done in Hudy et al. (2007). The pressure data points are fitted by a 5th order polynomial equation without interpolation between the measurement locations, avoiding bias contamination by adding artificial information in the measured data. However, this also results in a reduced precision in the estimation of X_R (i.e. 0.15 h, the distance between two consecutive pressure sensors). In order to extend the parametric investigation to the unsteady character of the flow, a second metric is considered. The spatial integral of the wall pressure fluctuation coefficient $C_{P'}$ is performed all along the bottom wall (grey region in Fig. 2). This integral is an estimator of the global flow variations in the shear layer developing from the step corner and impinging on the bottom wall. It is considered that the amplitude and frequency of the pressure fluctuations at the bottom wall are mainly caused by the intensity and the integral length scale of the vortical flow structures and the flapping character of the reattaching flow as it is discussed in Cherry et al. (1984) and (1983). Then, higher values of $C_{P'}$, and thus higher values of the $C_{P'}$ spatial integral, are supposed to be related to a new organization or amplification of the unsteady character of the separated flow.

This study includes time-resolved particle image velocimetry measurements. These measurements have been only performed for the optimal control parameters identified by the parametric investigation. The flow downstream of the BFS is measured by a fast PIV system composed by a high-speed camera (Photron, APX-RS), a single head Nd:YLF high-speed laser (Quantronix, Darwin-Duo), a triggering unit (EG, R&D Vision) and a PC running Davis V8.2 software (Lavision). The laser (laser sheet of 1 mm) is

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