Journal of Fluids and Structures ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Fluids and Structures

journal homepage: www.elsevier.com/locate/jfs

Minimization of time-averaged and unsteady aerodynamic forces on a thick flat plate using synthetic jets

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ARTICLE INFO

Article history:
Received 18 February 2014
Accepted 15 December 2014

Keywords:
Flow control
Synthetic jet
Unsteady aerodynamic forces
PIV

ABSTRACT

This article reports an experimental investigation on the reduction of the aerodynamic forces on a model consisting of an elongated blunt trailing edge plate using an active control system based on an open-loop, periodic actuation using synthetic jets. Measurements using PIV were conducted at two Reynolds numbers Re_h, based on the thickness of the plate h, of about 7200 and 14 400. The control arrangement consisted of two synthetic jet actuators coupled to two slots placed symmetrically along the model base. The synthetic jets were operated either in-phase or anti-phase (180° out-of-phase) with actuation frequencies of 50 Hz and 100 Hz. Both in-phase and anti-phase actuations were found to be effective in vortex shedding suppression and achieved considerable reduction of the time-averaged drag coefficient, $\overline{C}_D$. For Re = 7200 and actuation frequency of 50 Hz, both in-phase and anti-phase actuations resulted in a negative $\overline{C}_D$, suggesting that the synthetic jets acted as a propulsive device. The effectiveness of both control strategies was further evaluated by their capability of reducing the amplitudes of the oscillating drag and lift (normal force) coefficients $\tilde{C}_D$ and $\tilde{C}_N$ respectively. The experimental results showed that the in-phase actuation decreased the amplitude of the oscillating drag coefficient by about 25% compared to that of the natural wake but $\tilde{C}_D$ remained periodic with a frequency of the actuation. More importantly, in-phase actuation was found to result in a considerable decrease (nearly by one order of magnitude) in the amplitude of the oscillating normal force coefficient, $\tilde{C}_N$. In contrast, the anti-phase actuation increased the amplitudes of both the oscillating lift and drag coefficients by nearly 95% and 30% respectively compared to the natural wake.

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1. Introduction

Flows past bluff bodies have been extensively investigated in the literature due to their fundamental importance in understanding aerodynamic drag, shear layer rollup and the subsequent formation of the Von-Karman vortex shedding in the wake. Bluff body flows are dominated by high frequency convective instabilities that dominate the separating shear layer and low frequency absolute instabilities that govern vortex shedding in the near wake. These instabilities make bluff body flows very attractive for flow control studies, namely to develop control techniques for the suppression of the vortex

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http://dx.doi.org/10.1016/j.jfluidstructs.2014.12.007
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Nomenclature

c	chord length of the model (mm)
h	thickness of the model (mm)
w	spanwise width of the model (mm)
w_A	spanwise width of the slots (mm)
e	thickness of slots (mm)
x,y,z	streamwise, transverse and spanwise coordinates, positioned at the centre of the model base
θ	momentum thickness of the boundary layer at the trailing edge (mm)
δ^*	displacement thickness of the boundary layer at the trailing edge (mm)
U_∞	free-stream velocity (m s^{-1})
U_d	mean streamwise velocity deficit (m s^{-1})
ℓ	wake width (mm)
ω_z	phase averaged spanwise vorticity
$u_{A,max}$	maximum actuation velocity at slot exit
f_v	vortex shedding frequency (Hz)
f_A	actuation frequency (Hz)
Re_h	Reynolds number based on model thickness ($U_\infty h/\nu$)
St	Strouhal number, fh/U_∞
C_μ	synthetic jet momentum coefficient
ϕ	phase angle (deg)
$\overline{C}_D$	time-averaged drag coefficient
$\overline{C}_N$	time-averaged normal force (lift) coefficient
$\tilde{C}_D$	oscillating drag coefficient
$\tilde{C}_N$	oscillating normal force (lift) coefficient
u	fluctuating component of streamwise velocity
v	fluctuating component of transverse velocity
$\overline{uu}$	streamwise Reynolds stress (m^2 s^{-2})
$\overline{vv}$	transverse Reynolds stress (m^2 s^{-2})
$\overline{uv}$	turbulent shear stress (m^2 s^{-2})

Abbreviations

PIV	particle image velocimetry
POD	proper orthogonal decomposition

shedding which has been shown to affect the pressure drag on blunt objects and to result in periodically oscillating aerodynamic forces. Passive and active flow control techniques in particular for a cylinder wake, have been reported in the literature over the past few decades. These techniques generally aim either at inhibiting vortex shedding or at preventing the interaction between the shear layers and the decoupling of the lower and upper vortex shedding so that the rolling up of vortices starts farther downstream.

Numerous passive control techniques have been applied to a cylinder wake for vortex shedding suppression; Bearman and Owen (1998) used different shapes placed at the stagnation surface of the bluff body; Strykowski and Sreenivasan (1990), Sakamoto and Haniu (1994), Dalton et al. (2001) and Thiria et al. (2009) placed a smaller cylinder to interfere with the shear layer rollup in the wake of a larger cylinder. The main finding is that in addition to the mean drag decrease, the oscillations of drag and lift were reduced by the presence of the secondary cylinder. Bearman (1965) and Yao and Sandham (2002) used a splitter plate placed on the axis of symmetry of a cylinder and found that the coupling of the opposite shear layers was inhibited and consequently, the drag was reduced. These flow control techniques have also been extended to include the wakes of elongated bodies having a blunt-trailing edge. Clearly, such techniques would be very beneficial for the so-called flatback or blunt-trailing edge airfoil applications such as wind turbine blades and supercritical airfoils. These airfoils have improved lift characteristics and structural integrity, but because of their blunt trailing edge, they generate higher pressure drag due to the periodic, low-pressure flow in their near-wake. Passive control techniques of flows over elongated bluff bodies have been reported in many investigations. For example, Tanner (1975) employed segmented, M-shaped and curved trailing edges; Grinstein et al. (1991) placed a splitter plate in the wake centreline; Tombazis and Bearman (1997) attached a set of wavy trailing edges; Park et al. (2006) attached equally spaced small tabs to the trailing edge; and others. In the above studies, significant drag reduction has been achieved by suppressing the interaction between the two separating shear layers and/or affecting the vortex shedding in the vortex formation region. Form drag reduction has also been achieved by modifying the flow momentum in the near wake of elongated bluff bodies either by trailing edge suction (Sharma and Sahoo, 1999) or blowing (Wu et al., 2008; Cimbala and Park, 1990). Cimbala and Park (1990) have shown that a proportioned injection from a slit in the middle of the model base spanning the whole width of the trailing edge of a flat plate, achieved a “momentumless” wake with no vortex shedding. In a later study, Park and Cimbala (1991) have shown that the momentumless wake dynamics strongly depended on the slit configuration of injection. They observed that blowing from dual slots symmetrically positioned about the base centre was different from a single slit blowing in terms of spreading rate and turbulence intensity magnitudes.

These passive means are reliable because of their simplicity and cost effectiveness. However, when operating under off-design conditions these static systems may induce undesirable effects. Active flow control techniques may further improve performances by adapting the actuation to a wide range of operating conditions. Active control of bluff body wakes has been reported in a number of papers in which a variety of techniques have been proposed. Among these, one may cite oscillating bluff body (Choi et al., 2002; Lu et al., 2011); oscillating wake splitter plate (Wu and Shu, 2011; Sudhakar and Vengadesan, 2012); plasma actuation (Timothy et al., 2009); pulsed jets (Williams and Amato, 1989); synthetic jets (Amitay et al., 1998). The latter authors showed that the separation point may be moved by approximately 60° resulting in a 25% reduction in form drag. A more comprehensive account of passive and active flow control studies on cylinder flows can be found in Gad-el-Hak (2000), Choi et al. (2008), Jukes and Choi (2009) and Cattafesta III and Sheplak (2011).

Please cite this article as: Ben Chiekh, M., et al., Minimization of time-averaged and unsteady aerodynamic forces on a thick flat plate using synthetic jets. Journal of Fluids and Structures (2015), http://dx.doi.org/10.1016/j.jfluidstruct.2014.12.007

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