CONTROL OF VORTEX INDUCED VIBRATION OF A CIRCULAR CYLINDER

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ABSTRACT

We investigate the effects of three flow control schemes – suction only, blowing only, and combined windward suction/leeward blowing – on the fluctuating lift of a stationary circular cylinder and on the free oscillation of a cylinder subject to vortex induced vibrations. We report results of three-dimensional direct numerical simulations, and show that overall the combined suction/blowing control is the most effective amongst the three. With this control, the r.m.s. *lift coefficient decreases linearly with increasing blowing/suction velocity for suction/blowing velocities below a certain value, and beyond that point the lift coefficient becomes essentially negligible. Simulation of a freely vibrating cylinder shows that the cross-flow cylinder oscillation decreases with increasing blowing/suction velocity and is completely suppressed at high blowing/suction velocities.*

1. INTRODUCTION

Vortex-induced vibration (VIV) of cylindrical structures is crucial to many engineering applications. A high level of fatigue damage to the structures can be produced by VIV in a relatively short period of time. In recent years a great deal of efforts have been devoted to the understanding and prediction of VIV with the ultimate goal of its prevention; see the reviews by Williamson & Govardhan (2004) and Sarpkaya (2004) and the references therein. The unsteady cross-stream force, the fluctuating lift, acting on the structure is the primary source of the flow-induced oscillations. Suppressing the fluctuating lift on a cylinder is therefore of tremendous importance and can potentially lead to practical methods for the ultimate prevention of undesirable VIVs.

Among the many techniques for manipulating the near-wake structure of a circular cylinder for flow control are the use of a splitter plate (Roshko, 1961), forced rotary motion (Berger, 1967; Tokumaru & Dimotakis, 1991), feedback control (Roussopoulos, 1993; Park *et al.*, 1994; Wolfe & Ziada, 2003), base bleed (Wong, 1985), local injection of a viscoelastic fluid (Cadot & Lebey, 1999), cylinder heating (Wang *et al.*, 2000), synthetic jets (Glezer & Amitay, 2002), small vibrating rod or control cylinder (Huang *et al.*, 2006; Mittal & Raghuvanshi, 2001), introduction of perturbation vortices (Tang & Aubry, 2000), and attached O-rings (Lim & Lee, 2004); see also Zdravkovich (1981) for a review of the passive control methods. Blowing or suction as a means for drag reduction or vortex manipulation is the subject of several previous studies (Williams *et al.*, 1992; Park *et al.*, 1994; Lin *et al.*, 1995; Min & Choi, 1999; Delaunay & Kaiksis, 2001; Mathelin *et al.*, 2001*a*). Lin *et al.* (1995) investigated the effects of steady blowing and unsteady blowing/suction of fluid through small holes arranged in a helical pattern on the cylinder surface experimentally. It was observed that the near-wake structures were significantly altered by the control for a stationary cylinder. When the flow control was applied simultaneously with a forced harmonic oscillation of the cylinder, however, even at a relatively low oscillation amplitude the latter dominated the process and the effects of steady blowing or unsteady blowing/suction control seemed to vanish in the range of parameters studied. Williams *et al.* (1992) experimentally studied the effects of unsteady ejection or suction of fluid through two rows of small holes, parallel to the cylinder axis, on the cylinder surface at an angle $\pm 45^0$ from the front stagnation line. They observed that the produced localized disturbances modified the vortex shedding patterns and frequencies as well as the chatacteristics of the mean flow profiles. Employing two-dimensional numerical simulations, Delaunay & Kaiksis (2001) investigated the effect of steady suction or blowing applied at the cylinder base around the Reynolds number $Re = 47$, at which the steady flow transitions to an unsteady state with vortex shedding. They showed that in the supercritical regime ($Re > 47$) slight blowing or high enough suction stabilized the wake while in the subcritical regime suction destabilized the wake and blowing had no detectable effect on the flow stability. The thermal and dynamic behavior of a cylinder in a heated turbulent cross flow, subject to blowing of cold fluid through its porous surface, was studied experimentally (Mathelin *et al.*, 2001a,b) and with two-dimensional numerical simulations (Mathelin *et al.*, 2002). Blowing drastically reduced the thermal flux and the wall temperature, providing an effective thermal protection of the wall. The Strouhal number was observed to decrease with the injection ratio until a saturation state was reached. Fransson *et al.* (2004) measured the effects of uniform blowing or suction on the turbulence statistics for the flow past a porous cylinder at Reynolds numbers around 10^4. The drag was observed to increase linearly with the blowing rate while for suction there was a drastic decrease at a specific suction rate when the separation line moved towards the rear part of the cylinder. More recently, Kim & Choi (2005) numerically investigated a forcing scheme for cylinder drag reduction by blowing or suction of fluid, whose intensity was sinunoidally modulated along the cylinder axis, through two slits placed on the top and bottom cylinder surfaces (at an angle around $\pm 90^0$ from the front stagnation line) respectively. It was observed that the in-phase forcing at the two slits reduced the drag substantially and could also attenuate or annihilate the Karman vortex shedding.

Studies of the above flow control techniques, including blowing or suction and the other techniques, have so far been confined to the context of flows past stationary cylinders. While several techniques seem capable of suppressing the vortex shedding in the wake of a stationary cylinder, the effect is not clear for cylinders subject to vortex induced vibrations. Indeed, it has been shown for wavy cylinders and cylinders with bumps that even though the vortex shedding can be suppressed when the cylinder is stationary, significant amplitudes of oscillation still develop if the cylinder is allowed to freely vibrate (Owen & Bearman, 2001; Bearman & Brankovic, 2004).

In this paper we investigate the effects of three flow control schemes – suction, blowing, and a new scheme combining suction and blowing – on the fluctuating lift of a stationary circular cylinder, and on the free oscillation of a cylinder subject to vortex induced vibrations. With the combined suction/blowing control, suction is applied on the windward half of the cylinder surface while blowing is applied on the leeward half of the surface. This scheme will be referred to as the WSLB scheme hereafter in this paper. Employing three-dimensional direct numerical simulations (DNS) at a Reynolds number $Re = 500$, we demonstrate that overall the WSLB scheme is the most effective among the three in terms of reducting the fluctuating lift. The underlying reasons for the lift/VIV reduction/suppression will be explored.

2. SIMULATION PARAMETERS

We consider the flow past a long rigid circular cylinder under two situations: (1) The cylinder is stationary (stationary case); (2) The cylinder is allowed to freely vibrate, but only in the cross-flow direction (VIV case). The cylinder axis is aligned with the z-axis of the coordinate system (assumed to be homogeneous in z direction, or spanwise direction), and the incoming flow is assumed to be in the x-direction (streamwise direction). We solve the three-dimensional incompressible Navier-Stokes equations by employing a Fourier spectral expansion of the flow variables in the homogeneous spanwise direction and a spectral element discretization in the two-dimensional streamwise-crossflow planes. For the VIV case, a coordinate system attached to the axis of the cylinder is used and the cylinder becomes stationary in this system. Details of the numerical methods for the stationary case and VIV simulations are documented in Dong & Karniadakis (2005), Dong *et al.* (2006) and Newman & Karniadakis (1997). For time integration we employ a stiffly-stable velocity correction-type scheme with a third-order accuracy in time (Karniadakis *et al.*, 1991).

At the inlet is a prescribed uniform inflow. Neumann boundary condition is applied at the outflow, and periodic boundary condition is used in the cross-flow (y) direction. For the WSLB control, steady suction and blowing are applied on the windward half and the leeward half of the cylinder surface, respectively. For pure blowing (or pure suction) control, steady blowing (or suction) is applied on the entire cylinder surface. These controls are characterized by a blowing/suction velocity normal to the cylinder surface with a uniform magnitude (referred to as control velocity magnitude, $V_{control}$, hereafter). Dirichlet boundary condition is applied on the cylinder surface in accordance with the flow control. For cases without control, the no-slip condition is imposed on the cylinder surface.

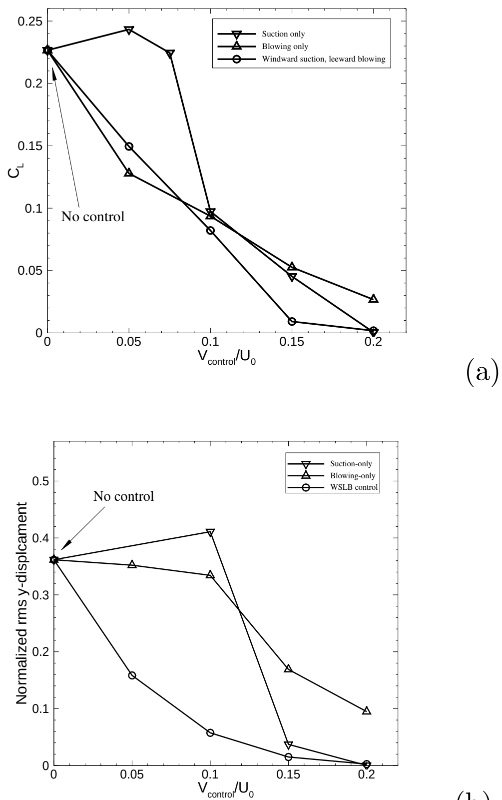
Three-dimensional direct numerical simulations (DNS) are conducted at the Reynolds number $Re = 500$, based on the free-stream velocity U_0 and the cylinder diameter D. The computational domain extends from $-20D$ at the inlet to $40D$ at the outlet, and from $-20D$ to $20D$ in the crossflow direction. The spanwise dimension of the flow domain is $L_z = 3\pi D$. Extensive grid refinement tests have been conducted. We employ a spectral element mesh with 1860 quadrilateral elements in the streamwise-crossflow planes, and the element order varies from 4 to 6. In the spanwise direction we employ 64 to 96 Fourier modes (or 128 to 192 grid points), all with 3/2-dealiasing. Based on the friction velocity at the top tip of the cylinder, $(x, y) = (0.0, 0.5D)$, these parameters lead to grid spacings near the cylinder surface of 0.05 in the radial direction, 0.3 in the azimuthal direction, and 2.3 in the spanwise direction in viscous wall units for $Re = 500$; The global physical parameters (drag coefficient, lift coefficient, Strouhal number) from the simulations for a stationary cylinder, without control, are in good agreement with the experimentally determined values from literature (Wieselsberger, 1921; Norberg, 2003).

3. RESULTS

Pure suction, blowing, and the WSLB control significantly affect the fluctuating lift force on the cylinder. Applying the control has reduced the amplitude of the fluctuating lift force substantially. We systematically vary the magnitude of the control velocity and investigate the effect on the fluctuating lift of the cylinder (stationary case). Figure 1(a) compares the root-mean-square (*r.m.s.*) lift coefficient as a function of the normalized control velocity ($V_{control}/U_0$) with the three controls. The overall observation is that the fluctuating lift is significantly reduced with the flow controls, and even completely suppressed at high control velocities. However, the three schemes exhibit quite different characteristics. Pure suction is only effective for lift reduction at high suction velocities ($V_{control}/U_0 = 0.1$ or above). Low suction velocity, on the other hand, appears to have the opposite effect; With a suction velocity $V_{control}/U_0 = 0.05$, the *r.m.s.* lift coefficient is increased somewhat. For the WSLB control, the *r.m.s.* lift coefficient decreases linearly with increasing blowing/suction velocity below a certain control velocity value ($V_{control}/U_0 = 0.15$). Beyond this point the r.m.s. lift coefficient becomes essentially negligible. Both the WSLB control and the pure suction can completely suppress the fluctuating lift at the highest control velocity considered here ($V_{control}/U_0 = 0.2$). At the same control velocity values, the WSLB scheme appears to be more effective than pure suction in terms of lift reduction. With pure blowing, the lift coefficient decreases with increasing control velocity. At the lowest control velocity ($V_{control}/U_0 = 0.05$), pure blowing appears the most effective among the three schemes. However, as the control velocity increases it becomes less effective compared to the other two. At the highest control velocity considered here ($V_{control}/U_0 = 0.2$) the fluctuating lift still remains quite significant with the pure blowing control. Overall, the WSLB control appears the most effective in terms of lift reduction among the three schemes. At low control velocities it avoids the lift increase as observed with pure suction, and at high control velocities it produces a high rate of reduction unlike the pure blowing control.

Since the ultimate goal is to reduce the VIV, we have simulated the flow past a freely vibrating cylinder (in cross-flow direction only) at $Re = 500$ to verify the effectiveness of the flow control in reducing VIV. Two cases have been simulated: without control and with the flow controls. Figure 1(b) shows the *r.m.s.* displacement of the cylinder in the cross-flow direction as a function of the control velocity for a structural damping coefficient 0.0046. This is for a cylinder mass ratio (with respect to the fluid) of 5.09. The inherent frequency of the cylinder oscillation is set to be equal to the Strouhal frequency of the flow past a stationary cylinder at the same Reynolds number. Suction-only control becomes only effective at high control velocities. In fact, an increase in the oscillation amplitude is observed at low control velocities ($< 0.1U_0$). Although a consistent decrease in oscillation amplitude is observed with the blowing-only control, the rate of decrease is considerably smaller than the other controls, and a significant amount of oscillation can still be observed at the highest control velocity considered here with this control. With the WSLB control, it is observed that the cylinder oscillation amplitude decreases consistently with increasing control velocity. At high control velocities the cylinder oscillation is completely suppressed.

We have performed the stability analysis for the flow past a stationary cylinder using the method in Triantafyllou *et al.* (1986). By solving the Orr-Sommerfield equation on the mean streamwise velocity profiles at different downstream locations, the coordinates of the "criti-



(a)

(b)

Figure 1: Lift/VIV reduction: (a) *r.m.s.* lift coefficient C_L as a function of the normalized control velocity $V_{control}/U_0$ for the stationary case. (b) *r.m.s.* cylinder displacement in cross-flow direction as a function of control velocity for a freely vibrating cylinder subject to VIV.

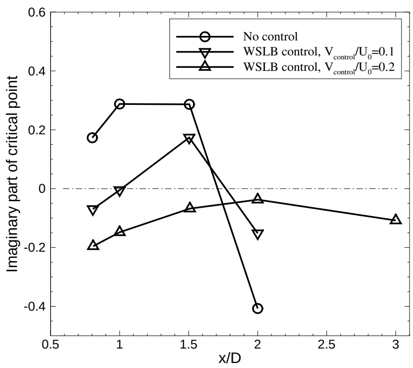


Figure 2: Stability analysis: Imaginary part of the critical point as a function of the streamwise location in the cylinder wake (positive values denoting absolute instability, negative values denoting convective instability).

cal point" (Triantafyllou *et al.*, 1986) in the ω-plane (ω is the complex frequency) can be determined. We computed the coordinates of the critical points based on the mean streamwise velocity profiles at different downstream locations for cases without control and with the WSLB control. Figure 2 shows the imaginary part of the critical point as a function of the streamwise location for several cases. Without control, we observe a region of absolute instability (positive ω_I) near the cylinder, and a region of convective instability further downstream (negative ω_I), consistent with Triantafyllou *et al.* (1986). With the WSLB control, the region of absolute instability is displaced downstream and shrinks in size. The nature of the instability in the near-wake region changes from an absolute instability (no-control) to a convective instability (see the case $V_{control}/U_0 = 0.1$). With increasing blowing/suction velocity, the highest ω_I value in the region of absolute instability also decreases, suggesting a decrease in the rate of growth of perturbations. At $V_{control}/U_0 = 0.2$, all the ω_I values have become negative, indicating a convective instability in the entire wake. As a result, the vortex shedding and the fluctuating lift are completely suppressed.

4. SUMMARY

We have studied a flow control scheme with steady suction on the windward half and steady blowing on the leeward half of the cylinder surface. It is shown that the r.m.s. lift coefficient decreases linearly with increasing blowing/suction velocity when the blowing/suction velocity is below a certain value. Simulation of a freely vibrating cylinder with controls demonstrates its effectiveness in reducing the VIV. At high control velocities the cylinder oscillation is completely suppressed. As to the effect on the drag, in the presence of the current control the drag force on the cylinder decreases by a small amount, about 5% in the range of parameters studied here.

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