CONTROL OF ABSOLUTE INSTABILITY BY LOCAL MEAN-FLOW MODIFICATION

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ABSTRACT

In the present study, we develop a method for controlling absolute instability based on variational calculus. In parallel wake exhibiting absolutely unstable nature, it is shown that the positive and negative velocity perturbations in basic flow, respectively, along the centerline and the separating shear layers suppress absolute instability. Using this method, we show that a secondary cylinder located at appropriate positions in the wake behind a main circular cylinder effectively suppress absolute instability in the near wake. It is also shown that the most effective position of the secondary cylinder suppressing absolute instability is along the separating shear layer.

INTRODUCTION

Understanding and controlling vortex shedding is very important in engineering applications because vortex shedding has significant effects in aerodynamic characteristics around vehicles and structures. Since Roshko (1955) has studied the periodic features of vortex shedding, many efforts have been devoted to understand and control vortex shedding. There have been many passive and active open-loop methods for the control of vortex shedding. Examples are base bleed (Wood, 1964), splitter plate (Roshko, 1955; Kwon and Choi, 1996), secondary cylinder (Strykowski and Sreenivasan, 1990), periodic rotation of cylinder (Tokumaru and Dimotakis, 1991; Choi et al., 2002), transverse oscillation of cylinder (Schumm et al., 1994), distributed forcing (i.e. active forcing whose magnitude varies in the spanwise direction.) (Kim and Choi, 2005), wake disrupter (small passive device disturbing wake in the spanwise direction) (Park et al., 2005) and so on.

Recently, a few active closed-loop ways of controlling vortex shedding have been investigated in the cylinder wake. Roussopoulos (1993) conducted proportional feedback control using a speaker based on the velocity phase information. A similar approach was also conducted by Park et al. (1994) using a pair of blowing/suction slots on the cylinder. However, those control strategies based on proportional feedback law could not achieve complete suppression of vortex shedding at relatively high Reynolds number since the control law destabilizes secondary linear global mode. A more systematic control method based on suboptimal feedback law (i.e. optimal control with infinitesimal time horizon objective function) was conducted by Min and Choi (1999). In this study, vortex shedding was completely suppressed up to $Re = 160$ by active forcing on the entire surface of the cylinder. More recently, a linear robust control strategy (i.e. optimal and robust control theory based on linearized equation) was applied to Ginzburg-Landau model which has similar bifurcation scenario to circular cylinder wake using a pair of actuator and sensor (Lauga and Bewley, 2004). They achieved complete suppression of self-sustained oscillation at low Reynolds numbers but the practical decay of stabilizability was discovered as the Reynolds number increases (Lauga and Bewley, 2003).

In general, closed-loop controls are more efficient and effective than open-loop controls, but they are quite difficult to implement in real applications. Therefore, in the final stage of controller development, one may require an open-loop control device rather than a closed-loop control device. The purpose of this paper is to develop a consistent open-loop control strategy in two-dimensional wake at low Reynolds number.

The dynamic behavior of open shear flow including wake has been commonly understood in the context of linear and nonlinear stability theory (Huerre and Monkewitz, 1990; Chomaz, 2005). In open shear flow, the Galilean invariance is broken by imposing boundary conditions (i.e. no-slip condition at solid wall). Therefore, one has to take account of the propagation of instability wave as well as its growth. In such a viewpoint the concept of absolute and convective instability is naturally introduced and their rigorous definition is originated from plasma physics (Briggs, 1964). If wave packet of infinitesimal amplitude spreads upstream and downstream and grows in time, the basic state is called linearly absolutely unstable. On the other hand, if wave pocket with the growing energy is swept away from the source, the basic state is called linearly convectively unstable. This concept was successfully applied to primary linear instability of parallel shear flow (Huerre and Monkewitz, 1985) and extended to weakly nonparallel shear flow (Huerre and Monkewitz, 1990 and references therein). Linear analyses in weakly nonparallel media revealed that linearly absolutely unstable regions are necessary for the onset of unstable linear global mode (i.e. temporally unstable eigensolution in entire nonparallel flow). Linear analyses successfully predicted local and global bifurcation scenario of cylinder wake (Monkewitz, 1988), but some questions mainly related to the effect of nonlinearity remained. Recently, those questions were solved by full nonlinear analyses (Chomaz, 2005 and references therein). In the same manner as the linear case, it was shown that linearly absolutely unstable regions are necessary for the existence of nonlinear global mode (e.g. vortex shedding in bluff body wake) in weakly nonparallel flow.

In view of flow control, local linear absolute instability dynamics has given critical information about the control mechanism of vortex shedding. For example, base bleed eliminates or weakens local absolute instability in near wake, and vortex shedding is suppressed (Schumm et al., 1994). Base suction of sufficiently large amplitude increases nonparallelism around dominant turning point in WKBJ approxmation, so vortex shedding is suppressed (Leu and Ho, 2001). Suppression of vortex shedding in the presence of small control cylinder has also been thought such that the mechanism is related to the change of local absolute instability in near wake (Strykowski and Sreenivasan, 1990).

As mentioned above, absolute instability plays critical roles in wake dynamics and control. Therefore, developing a systematic method for controlling absolute instability should help the development of open-loop control methods. In the present study, we formulate the control problem using calculus of variation and show that the suppression of vortex shedding from previous open-loop control methods such as base bleed and positioning small control cylinder is explained by the control of absolute instability.

PROBLEM FORMULATION IN PARALLEL WAKE

Variational calculus of absolute frequency

Linear impulse response in parallel media is dominated by absolute frequency (Huerre and Monkewitz, 1985). To calculate the first variation (i.e. Frechét derivative) of absolute frequency in the direction of basic-flow change, we consider the Orr-Sommerfeld equation:

$$-i\omega M\psi + L_{os}\psi = 0, \tag{1}$$

where

$$M = \alpha^2 - \mathcal{D}^2, \tag{2}$$

$$L_{os} = i\alpha U(\alpha^2 - \mathcal{D}^2) + i\alpha\mathcal{D}^2 U + \frac{1}{Re}(\alpha^2 - \mathcal{D}^2)^2, \tag{3}$$

and the boundary conditions are

$$\psi\Big|_{\partial\Omega} = \mathcal{D}\psi\Big|_{\partial\Omega} = 0. \tag{4}$$

Here, ψ is the streamfunction of the velocity disturbance or transverse component of velocity disturbance, α is the streamwise wave number, ω is the temporal frequency, $\mathcal{D} = d/dy$, y is the transverse direction, Ω is the flow domain in the transverse direction, and $\partial\Omega$ denotes the boundary of the domain Ω. Re is the Reynolds number. Let us introduce the following inner product:

$$< u, v >= \int_\Omega u(y)\overline{v}(y)dy, \tag{5}$$

where an overbar denotes the complex conjugate. Then the adjoint equation corresponding to (1) is given by

$$-i\omega^+ M^+\phi + L^+_{os}\phi = 0, \tag{6}$$

where

$$M^+ = (\overline{\alpha}^2 - \mathcal{D}^2), \tag{7}$$

$$L^+_{os} = -i\overline{\alpha}U(\overline{\alpha}^2 - \mathcal{D}^2) + 2i\overline{\alpha}\mathcal{D}U\mathcal{D} + \frac{1}{Re}(\overline{\alpha}^2 - \mathcal{D}^2)^2, \tag{8}$$

and the boundary conditions are

$$\phi\Big|_{\partial\Omega} = \mathcal{D}\phi\Big|_{\partial\Omega} = 0. \tag{9}$$

The superscript $^+$ denotes the adjoint operator and ϕ is the adjoint variable. In order to derive the first variation of complex absolute frequency, let us introduce the Frechét differential (Luenberger, 1969):

$$\frac{\mathcal{D}\omega}{\mathcal{D}U}\delta U \equiv \lim_{\epsilon\to 0}\frac{\omega(U(y)+\epsilon\delta U(y)) - \omega(U(y))}{\epsilon}. \tag{10}$$

Under the assumption that the complex absolute frequency denoted by ω_0 is one of the discrete eigenspectrum, the first variation of discrete temporal frequency can be written as follows:

$$\delta\omega \sim \frac{\partial\omega}{\partial\alpha}\delta\alpha + \frac{\mathcal{D}\omega}{\mathcal{D}U}\delta U =< L_{\delta\alpha}\psi, \phi > + < L_{\delta U}\psi, \phi >, \tag{11}$$

where

$$L_{\delta\alpha} = \delta\alpha\Big[U(3\alpha^2 - \mathcal{D}^2) + \mathcal{D}^2 U - 2\omega\alpha - i\frac{4\alpha}{Re}(\alpha^2 - \mathcal{D}^2)\Big], \tag{12}$$

$$L_{\delta U} = \alpha\delta U(\alpha^2 - \mathcal{D}^2) + \alpha\mathcal{D}^2(\delta U). \tag{13}$$

Applying (11) around the absolute frequency ω_0 eliminates the contribution of streamwise wavenumber variation since the absolute frequency ω_0 is selected by the pinching point condition: i.e. $\frac{\partial\omega}{\partial\alpha} = 0$ at $\alpha = \alpha_0$, where α_0 is the absolute wave number. Integration of (11) by part leads the following relation:

$$\delta\omega_0 \sim \frac{\mathcal{D}\omega_0}{\mathcal{D}U}\delta U = \int_\Omega K_0(y)\delta U(y)dy, \tag{14}$$

where

$$K_0(y) \equiv \alpha_0[\alpha_0^2\psi_0\overline{\phi}_0 + 2\mathcal{D}\psi_0\mathcal{D}\overline{\phi}_0 + \psi_0\mathcal{D}^2\overline{\phi}_0]. \tag{15}$$

Here, ψ_0 and ϕ_0 are the regular and adjoint eigenfunctions at the pinching point, respectively, and $K_0(y)$ is the Frechét derivative of absolute frequency and its physical meaning is the sensitivity of absolute frequency due to the change of basic flow. Similar formula based on classical linear stability problem was also obtained in Bottaro et al. (2003).

As known by Reddy et al. (1993), the eigenvalues of Orr-Sommerfeld operator are extremely sensitive to the perturbation of operator because the Orr-Sommerfeld operator is non-normal. Thus, (14) may appear to be unmeaningful for the control problem, because the small change of basic flow may make the other eigenvalues more destabilized than the absolute frequency. However, the non-normality of Orr-Sommerfeld operator at low Reynolds number is sufficiently moderate since the effects of self-adjoint viscous term are significant. This fact is also investigated based on ϵ pseudospectrum (not shown here). Therefore, $K_{0i}(y)$ plays critical roles in controlling absolute instability. Using $K_{0i}(y)$ one can determine $\delta U(y)$ in the stabilizing or destabilizing direction.

Optimal change of the parallel basic flow for stabilizing absolute instability

Using (14) we obtain the optimal modification of parallel basic flow. The growth rate of absolute frequency is the critical parameter for controlling absolute instability and its bifurcation characteristics. Therefore, one can construct the following optimization problem:

$$\min_{\delta U} \delta\omega_{0i} \quad \text{subject to} \quad \int_\Omega \delta U^2(y)dy = c, \tag{16}$$

where

$$\delta\omega_{0i} = \int_\Omega K_{0i}(y)\delta U(y)dy. \tag{17}$$

Here, c is reasonably smaller than 1. In the optimization problem (16), the equality constraint in (16) represents the condition of fixed energy input. Using the Lagrange multiplier, the optimally stabilizing solution δU can be obtained as follows:

$$\delta U(y) = -c\frac{K_{0i}(y)}{\sqrt{\int_\Omega K_{0i}^2(y)dy}}. \tag{18}$$

Application to parallel model wake at low Reynolds number

In this section, the formula derived in the previous sections is applied to model parallel wake at low Reynolds number. Regular and adjoint Orr-Sommerfeld equations are solved using the standard Chebyshev collocation technique with N=100 to ensure good resolution of all significant eigenvalues in the context of temporal setting. Velocities are non-dimensionalized with the average basic flow velocity $\widehat{U}^* = (U_c^* + U_\infty^*)/2$ where the superscript * denotes dimensional quantity, $U_c^* = U^*|_{y=0}$ is the centerline velocity, and $U_\infty^* = U^*|_{y=\infty}$ is the free stream velocity. Length is made non-dimensional with the local half-width b of the wake, which is defined by $U^*|_{y=b} = \widehat{U}^*$. The Reynolds number is defined as $Re_b = \widehat{U}^* b/\nu$. The profile of basic flow is as follows:

$$U(y) = 1 - \Lambda + 2\Lambda F(y), \tag{19}$$

where

$$\Lambda \equiv (U_c^* - U_\infty^*)/(U_c^* + U_\infty^*), \tag{20}$$

$$F(y) \equiv [1 + \sinh^{2N}\{y \sinh^{-1}(1)\}]^{-1}. \tag{21}$$

Here, we choose $\Lambda = -1.105$, $N = 1.34$. The corresponding velocity profile is shown in Fig. 1(a). Computation is performed at $Re_b = 12.5$. Absolute wave number is obtained as $\alpha_0 = 0.8075 - i0.4890$ and absolute frequency of regular and adjoint eigenvalue problems are $\omega_0 = 0.9577 + i0.0628$ and $\omega_0^+ = -0.9572 + i0.0627$.

As shown in Fig. 1(b), $K_{0i}(y)$ is positive in the separating shear layer and negative near $y = 0$. It is interesting to note that the presence of small control cylinder (Strykowski and Sreenivasan, 1990) results in $\delta U < 0$ and the flow becomes stabilized when the control cylinder is located where $K_{0i}(y) > 0$ (i.e., along the shear layer) (see (17)). On the other hand, the base bleed increases U along the centerline (i.e. $\delta U > 0$), and it suppresses local absolute instability at the location where $K_{0i}(y) < 0$ (i.e. along the center line). The base bleed was also known as suppressing absolute instability by previous parametric study in Monkewitz (1988), agreeing with the present result.

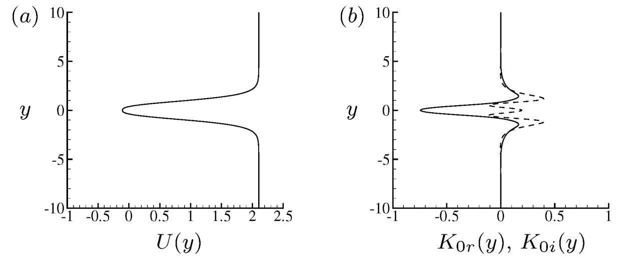

Figure 1: (a) Profile of the typical parallel basic flow ($\Lambda = -1.105$, $N = 1.34$); (b) Frechét derivative of absolute frequency ($Re_b = 12.5$). In (b) - - - -, $K_{0r}(y)$; ———, $K_{0i}(y)$.

ROLE OF A SMALL CONTROL CYLINDER IN CIRCULAR CYLINDER WAKE

Experimental results of Strykowski and Sreenivasan (1990) showed that vortex shedding is suppressed by a small control cylinder in the near wake of circular cylinder. Recently, Giannetti and Luchini (2003) showed by solving global eigenvalue problem numerically that the region of receptivity to global basic flow (i.e. entire nonparallel basic flow) modification is similar to the region where a small control cylinder effectively suppresses vortex shedding. However, it is still ambiguous about the role of the control cylinder in a local viewpoint (i.e. the dynamics of local absolute instability). Therefore, we investigate the role of the control cylinder on the local instability dynamics in this section.

Problem formulation in circular cylinder wake

The effect of a small control cylinder is modelled here as a pointwise supply of momentum equal in magnitude and opposite in direction to the drag on the control cylinder. Hence, the governing equation can be written as follows:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \tag{22}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{\partial p}{\partial x} + \frac{1}{Re_D}\triangle u + F(x,y,t;u), \tag{23}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{\partial p}{\partial y} + \frac{1}{Re_D}\triangle v, \tag{24}$$

where

$$F(x,y,t;u) = \epsilon\frac{C_R}{Re_d}u\delta(x-x_0)\delta(y-y_0)h(x_0,y_0), \tag{25}$$

$$h(x_0,y_0) = \begin{cases} -1 & \text{if } \bar{U}(x_0,y_0) > 0, \\ 0 & \text{if } \bar{U}(x_0,y_0) = 0, \\ 1 & \text{if } \bar{U}(x_0,y_0) < 0. \end{cases} \tag{26}$$

Here, the position of momentum supply is (x_0, y_0), $\epsilon \equiv d/D \ll 1$, where D and d are the diameters of main and control cylinders, respectively. $\bar{U}$ is the streamwise velocity of basic flow without the forcing term. Velocities are non-dimensionlized based on the free-stream velocity U_∞ and length is non-dimensionlized based on the diameter of main cylinder, $Re_D = U_\infty D/\nu$ and $Re_d = U_\infty d/\nu$. The forcing term F is considered

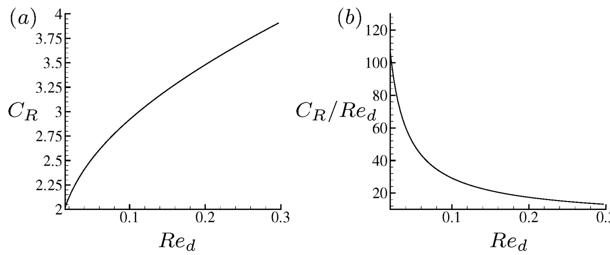

Figure 2: (*a*) C_R vs Re_d; (*b*) C_R/Re_d vs Re_d.

only in the streamwise direction to be included in local instability equation through the parallelization and linearization of governing equation. Therefore, the effect of the control in this study may not be exactly the same as that in the experiment of Strykowski and Sreenivasan (1990), especially where the transverse velocity of basic flow is relatively large or the streamwise velocity of basic flow is nearly zero. In (25), F sets to be proportional to u, since the portion of viscous drag in total drag of the control cylinder is dominant. Therefore, the resistance coefficient $C_R = drag/\mu U_\infty L$ which scales drag of the control cylinder and viscous force, is introduced in (25) rather than the drag coefficient $C_d = 2drag/\rho U_\infty^2 dL$, where L is the spanwise length of cylinder. To strictly model the effect of the control cylinder, C_R should be treated as a function of its position. In this study, however, C_R sets to be constant for the simplicity. The variation of C_R with Re_d is shown in Fig. 2(*a*).

Let the diameter of the control cylinder be so small that its wake effect can be negligible. Then the change of local instability is dominated at $x = x_0$. Therefore we can assume $\tilde{U} \sim \bar{U} + \epsilon\delta\bar{U}(x_0, y)$, where $\tilde{U}$ is the modified basic flow. For modelling $\delta\bar{U}$, it is also noteworthy that the velocity should be zero at the location of control cylinder by no-slip condition. Thus we can reasonably assume $\delta\bar{U}(x_0, y) \sim -\Pi(\epsilon(y - y_0))\bar{U}(x_0, y)/\epsilon$, where $\Pi(\epsilon y) \sim 1$ at $-\epsilon/2 < y < \epsilon/2$ and $\Pi(\epsilon y) \sim 0$ elsewhere. It is also assumed that $\Pi(\epsilon y)$ is at least twice continuously differentiable to avoid loosing regularity. Then, using a procedure similar to that described in the previous section, the first variation of local absolute frequency at $x = x_0$ is obtained as follows:

$$\delta\omega_0(y_0; x_0) \sim \delta\omega_{0F}(y_0; x_0) + \delta\omega_{0U}(y_0; x_0), \tag{27}$$

where

$$\delta\omega_{0F}(y_0; x_0) = -i\frac{C_R}{Re_d}h(x_0, y_0)\mathcal{D}\psi_0(y_0; x_0)\mathcal{D}\overline{\phi}_0(y_0; x_0), \tag{28}$$

$$\delta\omega_{0U}(y_0; x_0) = -U(y_0; x_0)K_0(y_0; x_0). \tag{29}$$

Here, $\psi_0(y_0; x_0)$, $\phi_0(y_0; x_0)$ and $K_0(y_0; x_0)$ are, respectively, regular and adjoint eigenfunctions and the Frechét derivative defined in (15) at the pinching point, based on the streamwise velocity of unforced local basic flow at $x = x_0$. $\delta\omega_{0F}(y_0; x_0)$ is the change of local absolute frequency due to the momentum forcing and $\delta\omega_{0U}(y_0; x_0)$ is its change related to basic-flow modification due to the momentum forcing. It is noteworthy that C_R/Re_d in (27) is the important parameter in determining the portion of $\delta\omega_{0F}$ in $\delta\omega_0$. Fig. 2(*b*) shows the behavior of C_R/Re_d vs Re_d. As shown in this figure, C_R/Re_d increases as Re_d decreases. Therefore, we can conclude that as the diameter of control cylinder becomes small, the portion of $\delta\omega_{0F}$ is dominant in $\delta\omega_0$. However, this divergence of C_R/Re_d at very small Re_d in $\delta\omega_{0F}$ does not mean the divergence of modified absolute frequency $\tilde{\omega_0} \sim \omega_0 + \epsilon\delta\omega_0$ because ϵ $(= d/D)$ also decreases as Re_d decreases.

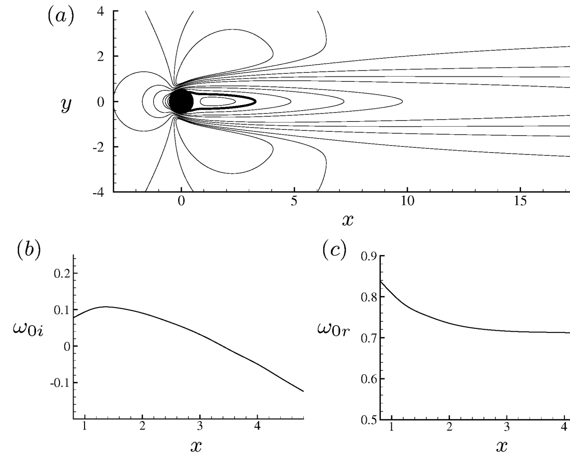

Figure 3: (*a*) Contours of the streamwise velocity of basic flow at $Re_D = 48$ (thick solid line, U=0); (*b*) imaginary part of local absolute frequency ω_{0i}; (*c*) real part of local absolute frequency ω_{0r}.

Position of control cylinder suppressing local absolute instability in circular cylinder wake at $Re_D = 48$

The equations are discretized on a Cartesian grid and the no-slip condition of a main circular cylinder is satisfied using an immersed boundary method developed by Kim et al. (2001). The center of the circular cylinder is located at $(x, y) = (0, 0)$. The number of grid points are 641×2048 in the streamwise and transverse directions, respectively. The excessive use of grid points in the transverse direction is to get high accuracy because the streamwise velocity is used to solve the Orr-Sommerfeld equation based on the Chebyshev collocation method. To obtain steady solution, upper half domain (i.e. $y \geq 0$) is considered and symmetric boundary conditions (i.e. $v = 0$ and $\partial u/\partial y = 0$) are imposed along $y = 0$. Uniform inflow conditions (i.e. $u = U_\infty$ and $v = 0$) are imposed at the inlet boundary and $u = U_\infty$ and $\partial v/\partial y = 0$ are imposed at the far-field boundary. The convective outflow condition is imposed at the exit. More numerical details are described in Kim et al. (2001).

The contours of streamwise velocity of basic flow at $Re_D = 48$ are shown in Fig. 3(*a*). The length of recirculation bubble is about $3.3D$ from the cylinder center and the drag coefficient is about 1.41, which show good agreements with the results in Fornberg (1985). To calculate local absolute frequency, the same numerical methods for solving regular and adjoint Orr-Sommerfeld equations are used. The streamwise velocity and its derivatives of basic flow for solving regular and adjoint Orr-Sommerfeld equations are obtained from the velocity field shown in Fig. 3(*a*) using a second-order linear interpolation. The complex local absolute frequency $\omega_0(x)$ is shown in Figs. 3(*b*) and 3(*c*) and the locally absolutely unstable region ($\omega_{0i} > 0$) is the nearly same as the reverse flow region.

Figures 4(*a*)-(*c*) show $\epsilon\delta\omega_{0i}(y_0; x_0)$, $\epsilon\delta\omega_{0Fi}(y_0; x_0)$ and $\epsilon\delta\omega_{0Ui}(y_0; x_0)$. They are negative along the separating shear layer. Therefore, the presence of control cylinder located at

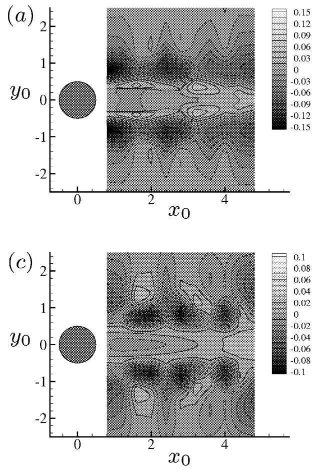

Figure 4: (a) $\epsilon\delta\omega_{0i}(y_0; x_0)$; (b) $\epsilon\delta\omega_{0Fi}(y_0; x_0)$; (c) $\epsilon\delta\omega_{0Ui}(y_0; x_0)$. Here $\epsilon = 1/12$.

the separating shear layer weakens or removes absolutely unstable regions in the near wake. In the reversal flow region, values of $\delta\omega_{0i}$, $\delta\omega_{0Fi}$ and $\delta\omega_{0Ui}$ are also negative. Thus, the presence of control cylinder and its wake along the center line suppresses absolute growth rate in the region of absolute instability and vortex shedding can be suppressed. However, one should note that the magnitudes of $\delta\omega_{0i}$, $\delta\omega_{0Fi}$ and $\delta\omega_{0Ui}$ inside the reversal flow region are relatively smaller than those along the shear layer. Therefore, the control cylinder located at the shear layer is more effective than that located inside the reversal flow region.

Figure 5 shows the result from Strykowsky and Sreenivasan (1990), representing the region where the addition of control cylinder completely restabilizes the cylinder wake at different Reynolds numbers. The region of stabilizing wake by the control cylinder obtained by Strykowski and Sreenivasan (1990) is quite similar to the negative regions of $\delta\omega_{0i}$ shown in Fig. 4(a).

CONCLUDING REMARKS

The concept of absolute and convective instability has played important roles in interpreting the dynamics and control mechanism in open shear flows such as wake, jet, mixing layer and boundary layer and so on. These critical roles of absolute and convective instability motivate us to develop a consistent strategy for controlling absolute instability based on variational calculus. Using the present methodology, in parallel wake exhibiting absolutely unstable nature, it is shown that positive and negative velocity perturbations, respectively, along the centerline and the separating shear layers suppress absolute instabilities. The present result shows a good agreement with previous one based on the parametric study in Monkewitz (1988). Finally, the suppression mechanism of vortex shedding by a small control cylinder located in the wake behind a main cylinder is investigated from the viewpoint of local instability. It is shown that the role of control cylinder is mainly related to the suppression of absolute instability in the near wake. The most effective position of control cylinder suppressing absolute instability is along the separating shear layers and these results are consistent with the experimental ones in Strykowsky and Sreenivasan (1990).

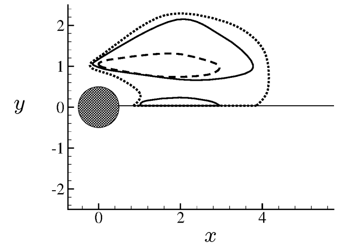

Figure 5: Regions where the presence of small control cylinder ($\epsilon = 1/10$) completely restabilizes cylinder wake: ·········, $Re_D = 46.2$; ———, $Re_D = 48$; - - - -, $Re_D = 50$.

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