Active Control of Flow over a Circular Cylinder

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Flow characteristics around a cylinder

- Steady flow (Re<47)
- 2-dimensional unsteady laminar flow (47<Re<160)
- Three-dimensional laminar flow: Re=220 (mode A: 160 ≤ Re ≤ 230)
- Three-dimensional laminar flow: Re=300 (Mode B; Re > 230)
- Turbulent flow in the wake: Re=3900

Numerical method (Choi, Moin & Kim, JFM 1993)
Flow characteristics around a sphere

- $Re=100$ (steady symmetric)
- $Re=250$ (steady planar symmetric)
- $Re=300$ (unsteady planar symmetric)
- $Re=425$ (unsteady asymmetric)
- $Re=3700$ (turbulent flow in the wake)
- $Re=10^4$ (turbulent flow in the wake)

Immersed boundary method (Kim, Kim & Choi JCP 2001)
Motivation

• Flow over a bluff body produces a significant amount of drag force and lift fluctuations and also generates flow-induced noise due to vortex shedding. Thus, there have been large amount of efforts devoted to control the flow around bluff bodies and to reduce the drag and lift.

• Many active and passive controls that are homogeneous in the spanwise direction have been presented: base bleeding, splitter plate, secondary small cylinder, rotation, single frequency forcing, electromagnetic forcing, some active blowing/suction based on sensing of flow variables (e.g. Min & Choi, JFM 1999).

Direct interaction with mean flow
Or with two-dimensional instability
Motivation

Turbulent flow over a backward-facing step (Kang & Choi, JFM 2002):
80% mixing enhancement using suboptimal control

- Wall pressure sensing
- Blowing/suction at the tip
- Generation of strong three-dimensional flow

Blowing/suction profile → Sine curve → Active open-loop control (Distributed forcing)

Laminar flow over a backward-facing step
(Choi, Hinze & Kunisch, ANM 1999)
Objectives

• In the present study, the possibility of applying an active control, which is varying in the spanwise direction (i.e. distributed forcing), to flow over a bluff body for drag reduction is investigated for a wide range of Reynolds numbers.

• Based on a successful active control method, we also develop a passive device for reduction of drag on a bluff body.

Circular cylinder
Model vehicle
Distributed forcing: cylinder

- Grid system: C-type grid
- Boundary conditions
  - uniform flow at inlet and far-field
  - convective outflow
  - periodic in the spanwise direction
  - blowing/suction at top and bottom slots
- Schematic of forcing
  - forcing profile: steady in time & periodic in z
  \[ \phi(z) = \phi_{\text{max}} \sin \left( 2\pi \frac{z}{\lambda_z} \right) \]
  - forcing phase: in-phase forcing, out-of-phase forcing
Distributed forcing : cylinder

- Effects of the spanwise wavelength ($\lambda_z$), forcing phase (in-phase vs. out-of-phase) and forcing amplitude (\(\phi_{\text{max}}\)) on the flow are considered for Re=100.

- Reynolds numbers considered
  - Re=40 : 2D, steady flow
  - Re=80,100,140 : 2D, unsteady flow
  - Re=220 : 3D unsteady flow with Mode-A instability
  - Re=300 : 3D unsteady flow with Mode-B instability
  - Re=3900 : turbulent wake (LES)

- Number of grid points
  - Re < 140 : 320 x 120 (x 16)
  - Re = 220, 300 : 320 x 120 x 48
  - Re = 3900 : 672 x 160 x 64
Distributed forcing: cylinder (Re=100)

- Effect of the spanwise wavelength $\lambda_z$

- Other parameters: $\phi_{max} = 0.1U_\infty$, in-phase forcing

- Time history of the drag coefficient

- Drag is minimum at $\lambda_z/d = 4$ to $5$.

- This wavelength is similar to that of the mode-A instability.

- Maximum drag reduction is 20%

  cf. Wavy cylinder by Darekar & Sherwin (2001, JFM): $\lambda_z/d = 5.6$ (16% DR).
Distributed forcing : cylinder (Re=100)

- Instantaneous flow structures (iso-surface of $\lambda_2 = -0.02$)
- Parameters: $\phi_{max} = 0.1U_\infty$, in-phase forcing

\[
\begin{align*}
\lambda_z &= 1d \\
\lambda_z &= 2d \\
\lambda_z &= 3d \\
\lambda_z &= 4d \\
\lambda_z &= 5d \\
\lambda_z &= 6d \\
\lambda_z &= 10d
\end{align*}
\]
Distributed forcing: cylinder (Re=100)

- Effect of the phase difference between upper and lower forcing
- Other parameters: \( \phi_{\text{max}} = 0.1U_\infty, \lambda_z = 5d \)

- Time history of the drag coefficient

- Vortical structures
  - Out-of-phase forcing
  - In-phase forcing
Distributed forcing : cylinder (Re=100)

- Effect of the forcing amplitude $\phi_{\text{max}}$
- Other parameters: $\lambda_z = 5d$, in-phase forcing

• Time history of the drag coefficient

\[ C_D \]

\[ \phi_{\text{max}} = 0.01U_\infty \]

- Mean drag coefficient

\[ \overline{C_D} \]

\[ \phi_{\text{max}} / U_\infty \]

saturation

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Distributed forcing : cylinder (Re=100)

- Spanwise variations of the base pressure coefficient and the separation point for the in-phase forcing

- base pressure coefficient

- separation point
Distributed forcing: cylinder ($Re=80, 140$)

- The base flow is 2-D laminar with Karman vortex shedding
- Parameters: $\phi_{\max} = 0.1U_{\infty}$, in-phase forcing

- Time history of the drag coefficient, $Re=80$
  - Drag is minimum at $\lambda_z/d = 5$ to 6

- Time history of the drag coefficient, $Re=140$
  - Drag is minimum at $\lambda_z/d = 4$ to 5
Distributed forcing : cylinder (Re=40)

- When \( Re = 40 \), there is no vortex shedding and distributed forcing does not work.

- Time history of the drag coefficient, \( Re=40 \)

- Flow structures
Distributed forcing : cylinder (Re=220)

- At Re=220 (mode A), $\phi_{max} = 0.1U_\infty$

- Time history of the drag coefficients

- Flow structure

Uncontrolled

In-phase, $\lambda_z = 3.75d$

In-phase, $\lambda_z = 1.875d$
Distributed forcing : cylinder (Re=300)

• At Re=300 (mode B), $\phi_{\text{max}} = 0.1U_\infty$

• Time history of the drag coefficients

• Flow structure
  - Uncontrolled
  - In-phase, $\lambda_z = 3d$
Distributed forcing : cylinder (Re=3900)

• Turbulent flow

• Parameters : \( Re = 3900, \phi_{max} = 0.1U_{\infty}, \frac{\lambda_c}{d} = \pi \)

• Time history of the drag coefficient

• Time history of the lift coefficient
Distributed forcing: cylinder (Re=3900)

- Instantaneous flow structures
  - Uncontrolled
  - Out-of-phase forcing
  - In-phase forcing

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Mechanism of drag reduction due to the in-phase forcing

- Small \( \lambda_z \) (Re=100, \( \phi_{\text{max}} = 0.1U_\infty \), \( \lambda_z \leq 3d \))
  - Vortex shedding frequency is the same at all the spanwise positions.
  - Shedding process at maximum suction has a faster phase than that at maximum blowing.

- vortical structures (top view)
  - \( U_\infty \)
  - \( \lambda_z = d \)
  - \( \lambda_z = 2d \)
  - \( \lambda_z = 3d \)

- \( v \) trace at \((x,y)=(2.0d, 0.6d)\)

\[ \frac{dz}{\lambda_z} = \frac{\pi}{19.0} \]

\[ \frac{dz}{\lambda_z} \leq \frac{\pi}{68.0} \left( \text{Re}=100, \right) \]

Vortex shedding frequency is the same at all the spanwise positions.
Shedding process at maximum suction has a faster phase than that at maximum blowing.

Mechanism of drag reduction due to the in-phase forcing
Mechanism of drag reduction due to the in-phase forcing

- Optimal \( \lambda_z \) (Re=100, \( \phi_{\text{max}} = 0.1U_\infty, \lambda_z = 4 \sim 5d \))

- Phase difference between the suction and blowing positions gradually approaches to \( \pi \).
- Vortex shedding is dislocated completely.

- \( \nu \) trace at \((x,y) = (2.0d, 0.6d)\)

\[ V_t = 0.1 U_{\infty} \]

\[ \lambda_t = 0.5 \]

\[ \phi_{\text{max}} = 0.1 \]

\[ \lambda_z = 4 \sim 5d \]

\[ \pi \]

\[ \frac{\pi}{2} \]

Mechanism of drag reduction due to the in-phase forcing
Distributed forcing : cylinder (Re=100)

- Parameters: $\phi_{\text{max}} = 0.1U_\infty$, in-phase forcing, $\lambda_z = 5d$

- Iso-surfaces of spanwise vorticity $(\omega_z = \pm 0.8)$
Mechanism of drag reduction due to the in-phase forcing

• Large $\lambda_z$ (Re=100, $\phi_{max} = 0.1U_\infty$, $\lambda_z = 7d$)

- Different shedding frequencies appear at different spanwise locations.
  - Frequency at suction location is higher than that at blowing location
  - Modulation occurs at $St_{\text{modulation}} = St_{\text{suction}} - St_{\text{blowing}}$

• $v$ trace at $(x,y) = (2.0d, 0.6d)$

• Energy spectrum of $v$
Drag reduction due to the out-of-phase forcing

- At Re=3900, shear layers become thinner and more susceptible to external disturbances
  \[ \frac{\delta}{d} \approx 0.069 \quad \text{for Re=3900} \]
  \[ \frac{\delta}{d} \approx 0.277 \quad \text{for Re=100} \]

- Out-of-phase forcing:
  - works only for thin separating shear layer
  - additional three-dimensionality in the shear layer delays the vortex shedding
  - shedding processes are merely pushed downstream

• Contour of streamwise velocity in an y-z plane (x=0.5d)
Flow over a model vehicle

- The objective is to examine the applicability of the distributed forcing to flow over a bluff body with a blunt trailing edge (fixed separation).

(Tombazis & Bearman 1997)
Computational details (LES)

- \( \text{Re} = \frac{u_\infty h}{\nu} = 4200 \)  
  \( (\delta / h = 1.36) \)
- Domain size:  
  - \(-3 \leq x / h \leq 15\)
  - \(-29 \leq y / h \leq 29\)
  - \(0 \leq z / h \leq 4\)
- Number of grids:  
  \(350 (x) \times 240 (y) \times 64 (z)\)
Distributed forcing: model vehicle

In-phase forcing

\[ \Phi(z) = \Phi_{\text{max}} \sin \left( \frac{2\pi}{\lambda_z} \right) \]

\( \Rightarrow \) Steady blowing/suction

Out-of-phase forcing

\[ \Phi(z) = \Phi_{\text{max}} \sin \left( \frac{2\pi}{\lambda_z} \right) \]

\( \Rightarrow \) Steady blowing/suction
Distributed forcing: model vehicle

- Base pressure coefficient

\[
C_{pb} (y=0)
\]

<table>
<thead>
<tr>
<th></th>
<th>Uncontrolled flow</th>
<th>In-phase forcing</th>
<th>Out-of-phase forcing</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-\overline{C_{pb}})</td>
<td>0.50</td>
<td>0.35</td>
<td>0.50</td>
</tr>
<tr>
<td>Pressure recovery (%)</td>
<td>—</td>
<td>30%</td>
<td>0%</td>
</tr>
</tbody>
</table>

\(z/h\)

- blowing
- suction
Distributed forcing: model vehicle

- Vortical Structures

Uncontrolled flow

In-phase forcing

Out-of-phase forcing
Experimental setup for distributed forcing

- Model vehicle

(Tombazis & Bearman 1997)

- \( W=300 \text{mm}, \ h=60 \text{mm} \)
- \( \text{Re}_h = u_\infty h/\nu = 20000, 40000, 80000 \)
- Trip wires
Actuator for distributed forcing

- Two fans comprise 1 wavelength.
- Four fans are constructed within the entire span.
- The maximum velocity from the slit: 4.1 m/s in the absence of freestream.
- Forcing wavelength $\lambda_z \approx 2.5h$. 
Base pressure along the spanwise direction

- Base pressure was clearly increased with control.
- Base pressure was recovered more at the blowing location.
- Spanwise variation of base pressure became milder at Re_{h}=40000.
- The percentages of base-pressure recovery are about 36% and 18% at Re_{h}=20000 and 40000, respectively.
Wake disrupter – a new passive device

Distributed forcing: three-dimensional disturbances to the flow with nominally two-dimensional Kármán vortex shedding.

- Small-size rectangular body attached to a part of the trailing edge.
- Can be easily attached or removed.
- No control input is required.

Wake disrupter
Experimental setup for wake disrupter

- Model vehicle

- $W=300\text{mm}$, $h=60\text{mm}$

- $Re_h = U_\infty h/\nu = 20000$, 40000, 80000

- Trip wires

- $ly/h, lz/h = 0.017-0.66$

- 71 cases with different sizes of disrupters.

- Spanwise average of the 18 pressure values along $y=0$. 
Experimental setup for wake disrupter
Percentage of base-pressure increase ($Re_h=20000$)

Percentage of base-pressure increase

$$= \frac{(C_p - C_{po})}{C_{po}} \times 100$$

($C_{po}$: base-pressure coefficient without disrupter)

Optimum size:

$l_y/h = 0.2 \sim 0.25$, $l_z/h = 0.2 \sim 0.25$
Percentage of base-pressure increase \((Re_h=40000, 80000)\)

\[ Re_h = 40000 \]

Optimum size: \( l_y/h = 0.15 \sim 0.35, l_z/h = 0.15 \sim 0.35 \)
How about two-dimensional fence?

$Re_h=20000$

- Introduction of three-dimensional motion is essential for drag reduction.
Large eddy simulation at $Re_h=4200$

Immersed boundary method (Kim, Kim & Choi 2001)

\[
\begin{align*}
\mathbf{u} &= \mathbf{u}_\infty, \ \partial v / \partial y = \partial w / \partial y = 0 \\
\end{align*}
\]

Domain:
\[
\begin{align*}
-3 \leq x/h &\leq 15 \\
-29 \leq y/h &\leq 29 \\
-2 \leq z/h &\leq 2
\end{align*}
\]

Four sizes of wake disrupter
\[
\begin{align*}
(l_x/h, l_y/h, l_z/h) &= (0.2,0.2,0.2) \\
(l_x/h, l_y/h, l_z/h) &= (0.4,0.2,0.2) \\
(l_x/h, l_y/h, l_z/h) &= (0.2,0.4,0.2) \\
(l_x/h, l_y/h, l_z/h) &= (0.2,0.2,0.4)
\end{align*}
\]

Grid points:
\[
350(x) \times 240(y) \times 64(z)
\]

Grid points inside a wake disrupter:
\[
14(x) \times 18(y) \times 64(z)
\]

\[
\begin{align*}
Re_\theta &= u_\infty \theta / \nu = 670 \\
Re_h &= u_\infty h / \nu = 4200 \\
\delta / h &= 1.4, \ \theta / h = 0.186
\end{align*}
\]
Base pressure along the spanwise direction

Maximum base-pressure recovery is about 16% in spite of the differences in $\theta$ and $Re_h$ with the experiment.

⇒ Wake disrupter is an effective control method applicable to various Reynolds numbers.
Wake structures

- Iso-surfaces of pressure

Without disrupter

Large-scale, two-dimensional Karman vortex cores exist.

With disrupter

\((l_x,l_y,l_z) = (0.2,0.2,0.2)\)

Kármán vortex cores are broken up into smaller-scale vortices and the wake becomes completely three-dimensional.
Wake structures

- Wake disrupter substantially suppresses vortex shedding.
- The naturally occurring vortices right behind the body certainly disappear with disrupters.

Uncontrolled flow

\[(l_x/h, l_y/h, l_z/h) = (0.2, 0.2, 0.4)\]
base-pressure recovery: 16%

\[(l_x/h, l_y/h, l_z/h) = (0.2, 0.4, 0.2)\]
base-pressure recovery: 12%
Conclusions

- In the present study, we considered two different bluff bodies; a circular cylinder and a two-dimensional model vehicle.

- The distributed forcing (active control) produced a significant amount of drag reduction for both bodies at quite different Reynolds numbers, and the drag reduction was achieved by direct modification of vortical structures in the wake rather than separation delay.

- The wake disrupter (passive device) also produced a significant amount of drag reduction for the model vehicle (the same result is also expected for the circular cylinder).

- Both the distributed forcing and wake disrupter introduced the spanwise mismatch in the vortex shedding process (either phase difference or frequency difference); Overall vortex shedding was weakened due to the spanwise incoherency; Then, the base pressure was increased and drag was reduced.
How to realize the **distributed forcing from EM tiles**?

Top view

- One wavelength of forcing
- Cylinder
- Or massively separating flow such as an airfoil at a large angle of attack!