Open and closed-loop control of a triangular bluff body using rotating cylinders

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Abstract: The active control of vortex shedding from a bluff body consisting of three rotating cylinders in triangular arrangement is studied numerically and experimentally. The flow is characterized at low Reynolds number $Re \sim 4000 - 6000$. Open-loop cases are considered to understand the influence of maximum rotation rate Ω and the non-dimensional forcing frequency F^*, scaled by the cylinder radius R and the free-stream velocity U_∞. Feedback control is considered by acquiring the hot-wire sensor signal in the wake and using it for the cylinders rotation speeds update. Adaptive and robust controllers are also be designed for the closed-loop control. As the parametric space for the controllers parameters is very large, machine learning using genetic programming will be a major technique for the command law optimization.

Keywords: Flow control, Closed-loop control, Machine learning, Genetic programming

1. INTRODUCTION

Bluff body wakes represent an important subject of study and correspond to different practical applications. Vortex streets are generated in the wake, due to flow instabilities, and induce fluctuations in drag and lift forces. Large-scale vortical structures develop downstream the bluff body.

Forcing the bluff body rotation in order to control these structures is of significant interest for engineering applications. Okajima et al. (1975) first studied the effect of a rotating cylinder on the wake experimentally and numerically. When the cylinder rotation speed is driven sinusoidally at a forcing frequency corresponding the natural vortex shedding, a more significant change of the flow was observed (synchronization phenomenon). This study was complemented by other experimental (Tokumaru and Dimotakis (1991), Fujisawa et al. (1998), Protas and Wesfreid (2002)) and numerical (Choi et al. (2002), Bergmann and Cordier (2008)) works. The maximum rotation rate:

$$\Omega = \omega_{max} \frac{R}{U_\infty} \tag{1}$$

with ω_{max} the peak of the rotation speed, R the cylinder radius and U_∞ the free-stream velocity, and the non-dimensional forcing frequency:

$$S_c = f_c \frac{2R}{U_\infty} \tag{2}$$

with f_c the forcing frequency, and their influence on the wake, was of important interest in previous studies.

Feedback active control of the wake of a cylinder was also considered. Williams and Zhao (1989) first used hot-wire probes downstream the cylinder in opposed phases and a loudspeaker upstream to control the wake. The rms values of the hot-wire signals and its main peaks on the spectrum were drastically reduced. Two hot-wire probes were also used by Fujisawa et al. (2001) to control actively the rotation speed of the cylinder using a gain-based feedback loop. The velocity fluctuations and the spanwise correlation were reduced using the feedback phase control. The drag coefficient was also reduced compared to the stationary cylinder. The control parameters were also optimized in the same experiment by Fujisawa and Nakabayashi (2002) using a neural network. Compared to the flow without actuation, the drag force was reduced by 16 % and the lift force by 70 %.

The objective in the present study is to achieve an active feedback control of a bluff body using rotating cylinders. A geometry is designed using three rotating cylinders arranged as a triangular prism. The rotation rates of the cylinders are controlled individually. The rotation of cylinders allows to control directly the vorticity flux fed to the wake and thus modify the vortical structures of the vortex shedding. The experimental set-up of this geometry is presented in section 2.

2. EXPERIMENTS AND SIMULATIONS SET-UP

2.1 Flow and bluff body

The experiments were conducted in a Jet Stream 500 open-loop wind-tunnel from Interactive Instruments. The wind tunnel included a 0.4 m long test section with a squared cross-section of $W_{WT} \times H_{WT} = 0.127\text{m} \times 0.127\text{m}$. With the experimental set-up presented in §2.2, the wind-tunnel turbulence intensity is about 5 %. The freestream velocity can be accurately set between 0.5 and 35.8 m/s. A freestream velocity of $U_\infty = 2$ m/s is considered.

The two-dimensional bluff body model is placed at the inlet of the test section as shown in figure 1. It consists of three identical cylinders of diameter $R = 0.01$ m, forming an equilateral triangle oriented against the freestream direction. The master cross-section of the complete geometry is $W = 5R$ and will be considered in this study as the characteristic length of the bluff body. This length leads to a Reynolds number $Re = U_\infty W/\nu \sim 6000$. The three cylinders are mounted on bearings fixed on both top and bottom walls, and thus span the entire wind-tunnel height.

Bearings are used at the fixation at the walls to allow the cylinders to rotate. As explained in the introduction (§1), considering the rotation of the cylinders allows to act directly on the vorticity, instead of a complex interaction with the incoming boundary layer. Each cylinder is controlled independently by a brushless DC motor (BLWR112D) from Anaheim Automation. The motors can rotate up to 3700 rpm, for a torque of 0.05 N.m. The rotation speed and position of each motor are measured with an optical encoder.

2.2 Measurements

The wake characteristics without control and its behavior when the cylinders are rotating are investigated in

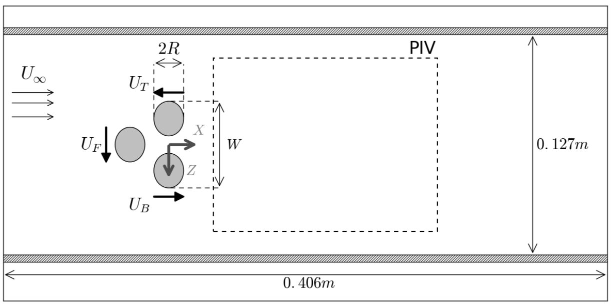

Fig. 1. Schematic of the experimental set-up and main dimensions of the geometry. The cylinders radius is $R = 0.01$ m and the master cross-section of the complete geometry is $W = 5R$. The origin is fixed at the middle between the symmetric cylinders.

this study. Two-dimensional two-components (2D2C) PIV experiments are conducted in the wake in a streamwise-spanwise plane as presented in figure 1. The measurement plane is located approximatively in the mid-height of the wind-tunnel ($Y = H_{WT}/2$). A Phantom Miro 340 camera is placed at 0.3 m above the measurement plane. The acquisition frequency is $f_{PIV} = 200$ Hz for a total field of 1600×1600 px^2. A Nikon lens with a focal of $f_o = 50$ mm is fixed on the camera. The magnification is $M = 0.16$ and the f-number $f_\# = 4$. A laser sheet of thickness $\delta_z \sim 2$ mm is realized using a pulsed Nd-YLF laser.

2.3 Simulations

URANS 2D-simulations are performed using the commercial software Fluent-ANSYS. A $k - \omega$ SST model for the turbulence is associated with these simulations. The total field simulated is $20W \times 8W$, centered at the body middle. The minimum meshgrid size is about $0.01W$. The time step is 500 μs (or about 250 time-steps per shedding cycles), for a total simulation time of about $10s$ (corresponding to approximatively 80 shedding cycles). Compared to experiments, similar flow conditions were chosen: $U_\infty = 1.5$ m/s and Reynolds number $Re \sim 4000$.

2.4 Closed-loop control set-up

Open-loop and closed-loop designs are presented in figure 2. The controlled system is the set { actuators, flow, sensors }, constituted with the motors driving the rotations, the response of the flow to this actuation and the sensors dynamics. All the elements of this system need to be considered. Due to the relative position of each element, the convection for example can introduce delays in the system and modify its modelling. The command vector $u(t)$ includes the rotation speeds $[\omega_f(t), \omega_b(t), \omega_t(t)]$ for the three cylinders. The output vector $y(t)$ is obtained by real-time measurements of the flow state, here the hot-wire or the pressure signals.

By fixing the rotation parameters (for example the amplitude,frequency, wave form, etc.), an open-loop control is performed. An optimization of the control performances using this set-up is however difficult to realize, in particular if the system considered is unstable, not perfectly modelled or submitted to perturbations. To increase the precision (for the tracking problem) or the robustness of the control,

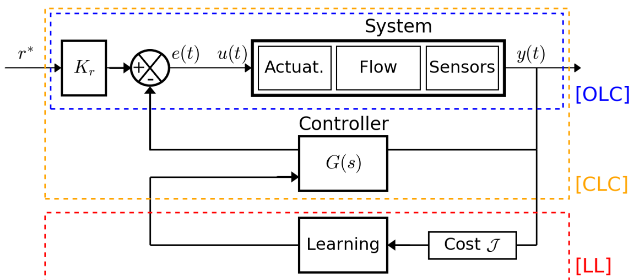

Fig. 2. Open-loop (OLC) and closed-loop (CLC) controls traditional shapes, and the learning loop (LL) for the controller optimization.

for example, a closed-loop control is preferred. The output vector $y(t)$ is acquired and compared to a reference value r^* in order to update the command vector $u(t)$ using the controller command law $G(s)$.

3. OPEN-LOOP RESULTS

The baseflow and few open-loop mechanisms are presented in this section. For each case, results from experiment and simulation with similar flow conditions are compared. U_F, U_T and U_B correspond to the surface speed for, respectively, front, top and bottom cylinders.

3.1 Baseflow

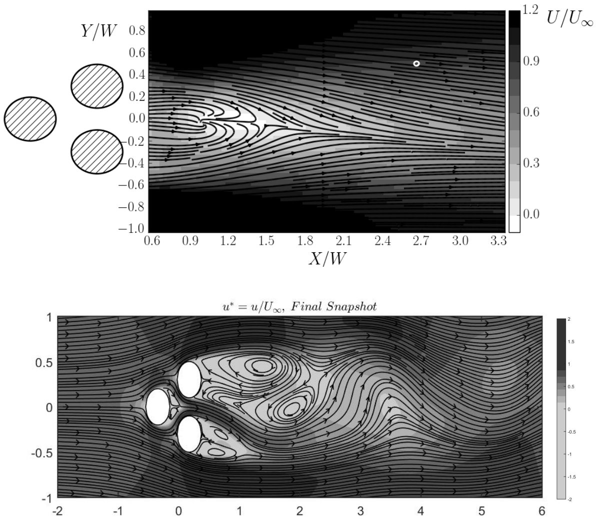

Fig. 3. **Baseflow without actuation:** No rotation, $U_F = U_T = U_B = 0$. Streamwise velocity U/U_∞, **(a)** Experiments at $U_\infty = 2$ m/s, **(b)** CFD at $U_\infty = 1.5$ m/s. The white circle corresponds to the spatial position chosen for spectral analysis.

The mean streamwise velocity for the flow without control is presented in figure 3 flooded as iso-contours and the streamlines are superposed. The averaged velocity on $N_s = 5400$ fields acquired experimentally at $U_\infty = 2$ m/s is presented in figure (a), the final snapshot for simulations at $U_\infty = 1.5$ m/s in figure (b). The three cylinders were fixed: $U_F = U_T = U_B = 0$. A large region of low-speed in the wake was observed for both results. However, downstream the gap between the two back cylinders of width equal to the cylinder radius, a 'jet' flow is present in the wake up to $X/W \sim 1$. The influence of the jet is similar to that a wake splitter plate on bluff-body flow for which the vortex shedding is delayed downstream (Apelt et al. (1973)).

Spectral analysis was also performed for the experimental results. The Power Spectral Density Function (PSDF) computed at $X/W = 2.66$ and $Y/W = 0.46$ using the streamwise velocity component is presented in figure 4. The spatial position of the spectrum is indicated in figure 3(a). A dominant trend of the power spectrum intensity can be observed around $St \sim 0.21$, indicating the signature

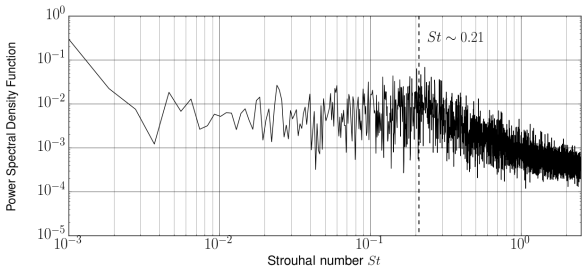

Fig. 4. Power spectral density function at $X/W = 2.66$ and $Y/W = 0.46$. This position is indicated with a white dot on figure 3(a).

of vortex shedding frequency. The same non-dimensional shedding frequency was found in simulations.

3.2 Boat tailing mechanism

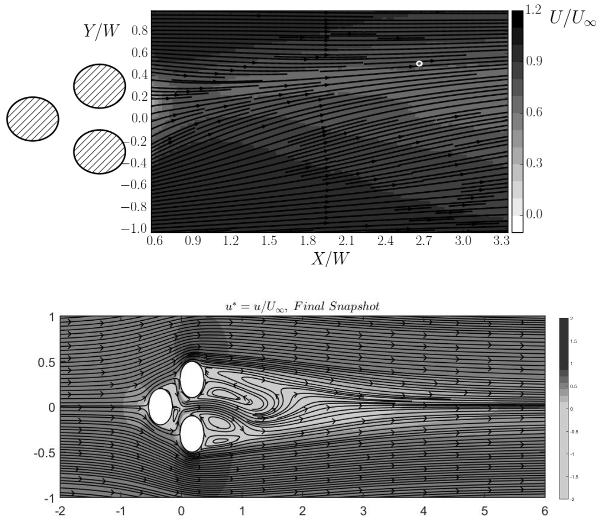

Fig. 5. **Boat tailing mechanism:** Constant speed, $U_F = 0$, $U_T = -U_B = -U_\infty$. Streamwise velocity U/U_∞, **(a)** Experiments at $U_\infty = 2$ m/s, **(b)** CFD at $U_\infty = 1.5$ m/s.

The same representation for streamwise velocity fields for the "boat tailing" mechanism are presented in figure 5. The rotating velocities for this mechanism are:

$$\begin{cases} U_F(t) = \quad 0 \\ U_T(t) = -\ U_\infty \\ U_B(t) = +\ U_\infty \end{cases} \tag{3}$$

This mechanism was found to be more efficient for suppressing shedding than other possible mechanisms. In both figures, a significant stabilization of the wake was observed. Shear layers were symmetrically tilted to the centerline and their streamlines converge between 2.5 (experiment) and 3 (simulation).

3.3 Oscillatory actuation

Oscillatory actuation is now considered. Compared to steady actuation, periodic excitation is believed to be

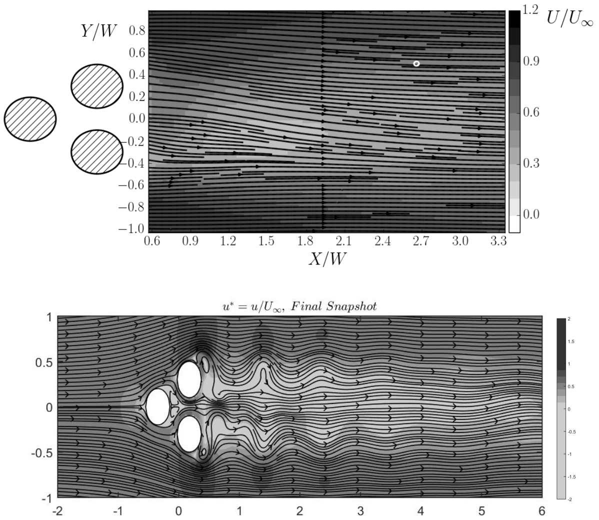

Fig. 6. **Oscillatory actuation:** $U_F = 0$, $U_T = U_\infty \ sin(2\pi f t)$, $U_B = U_\infty \ sin(2\pi f_c t + \pi)$. Streamwise velocity U/U_∞, **(a)** Experiments at $U_\infty = 2$ m/s and actuation frequency $F^* = f_c/f_{shedding} = 1$, **(b)** CFD at $U_\infty = 1.5$ m/s and actuation frequency $F^* = f/f_{shedding} = 3$.

more effective with less momentum of actuation injected (Greenblatt and Wygnanski (2000)). The front cylinder remains fixed, top and bottom cylinders are driven using periodic signals:

$$\begin{cases} U_F(t) = & 0 \\ U_T(t) = & U_\infty \ sin(2\pi f_c t) \\ U_B(t) = & U_\infty \ sin(2\pi f_c t + \pi) \end{cases} \tag{4}$$

with f_c the oscillation frequency. Velocity phases are separated by π and therefore cylinders rotate symmetrically. The dimensionless actuation frequency F^*, scaled by the shedding frequency $f_{shedding}$ found for the baseflow, is:

$$F^* = \frac{f_c}{f_{shedding}} \tag{5}$$

For the present study, $F^* = 1$ for experiment and 3 for simulation. Even if different frequencies of actuation are compared, the effect of periodic actuation is worthy of consideration. Streamwise velocity fields are presented in figure 6. As for the boat tailing mechanism, oscillatory actuation ensure clear wake stabilization. Freestream flow at cylinders position is significantly reduced in intensity and no reverse flow can be observed in the wake, suggesting better performances for wake stabilization than the tailing boat mechanism.

4. CLOSED-LOOP RESULTS

Linear feedback control using Proportional-Integral (PI) control was also performed for the simulation. Transient open-loop control was first simulated for circulation control expressed as:

$$U_F(t) = U_T(t) = U_B(t) = +U_\infty \tag{6}$$

The transient dynamics of the controlled flow for this case was characterized. By considering the spanwise velocity

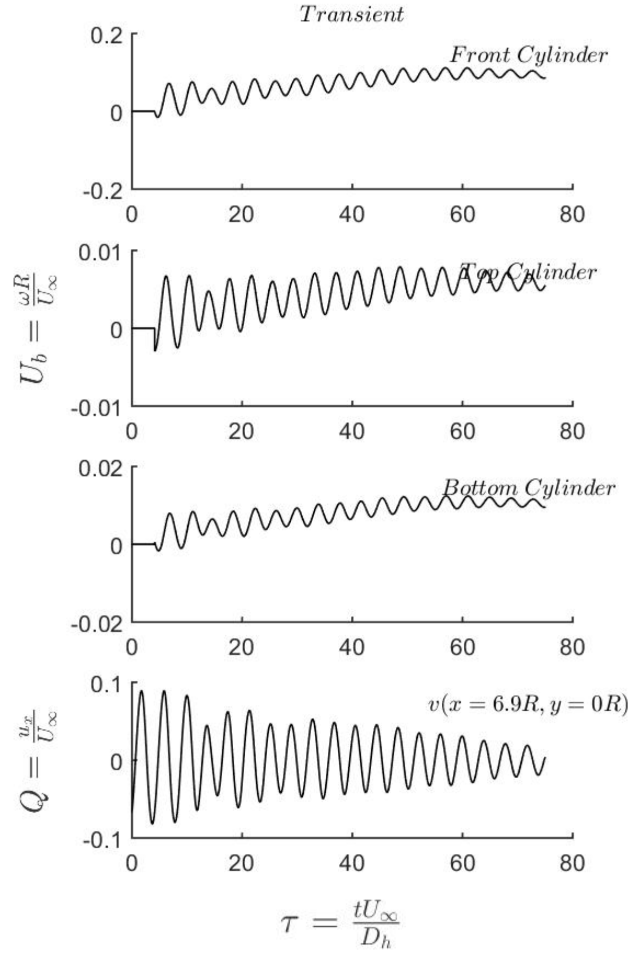

Fig. 7. Closed-loop preliminary results for PI control. Command variables (a) U_F, (b) U_T, (c) U_B (with $U_F = U_T = U_B$) and (d) controlled variable $v_s(t)$ scaled by U_∞

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component $v_s(t)$ at $X/W = 6.9$ and $Y/W = 0.6$ as feedback sensor, the characteristic rising time $\tau^* = \tau U_\infty / W$ and the delay $t_d^* = t_d U_\infty / W$ were estimated respectively as 0.56 and 2.16. From this response, the open-loop Ziegler-Nichols technique (Borne et al. (1993)) was applied and provided PI parameters:

$$\begin{cases} K_p = 53.1 & \text{m}^{-1} \\ K_i = 257.2 & (\text{m.s})^{-1} \end{cases} \tag{7}$$

and the feedback control law:

$$U_i(t) = R \left\{ K_p(r^* - u_s(t)) + K_i \int_0^t (r^* - u_s(\tau)) d\tau \right\} \tag{8}$$

with $i \in \{F, T, B\}$ and $r^* = 0$ the control target fixed arbitrarily by the user.

For a preliminary result, the command variables (a) U_F, (b) U_T, (c) U_B (equal considering circulation control) and (d) the controlled variable $v_s(t)$ are presented in figure 7. The velocity in the shear layer starts at the baseflow $v_s(t = 0)$ and shows periodic oscillations. With control, the amplitude of these oscillations is significantly reduced and almost disappear for $tU_\infty/W \sim 140$. To increase the wake stabilization, different feedback strategies based on the shedding phase will be considered as future perspectives.

CONCLUSION AND PERSPECTIVES

The control of the wake of a triangular bluff body modelled as rotating cylinders was investigated in the present study. The rotation allows to modify the vorticity flux to the wake. Here the control is direct, in terms of strength or time delay. The flow and influence of rotation were studied both experimentally and numerically. Respectively for experiment and simulation, the free stream velocity was $U_\infty = 2$ and 1.5 m/s, and the Reynolds number $Re \sim$ 6000 and 4000. The baseflow without control exhibited a large fluctuating wake region. Due to the gap between downstream cylinders, the flow acts as a jet and the vortex shedding is delayed downstream similarly to a splitter plate flow.

Open-loop was first considered by fixing the front cylinder and rotating the two other cylinders. The tailing boat mechanism, corresponding to a symmetric actuation $U_T = -U_B = U_\infty$, stabilizes significantly the wake downstream. Oscillating actuation ($U_T(t) = U_\infty\ sin(2\pi f_c t)$ and $U_B(t) = U_\infty\ sin(2\pi f_c t + \pi)$) allows to obtain better wake stabilization by minimizing the control cost. Linear feedback control was performed for simulation to stabilize and remove the oscillations observed in the spanwise velocity for the shear layer.

Closed-loop control will be performed with the experimental set-up. A hot-wire sensor will be introduced in the wake to have a local real-time measurement, and to be used as the control variable for the feedback controller. Different closed-loop controllers, from linear to adaptive and robust control, will be considered, for both experiment and simulations. From the baseflow and different open-loop cases, a proper definition of the objective functional $\mathcal{J}$ will be realized. This will be an important metrics for the comparison between different control cases. Machine learning control will also be implemented for the experimental set-up. Linear genetic algorithms has been proved to provide siginificant optimization of closed-loop controllers for flow control configurations (Duriez et al. (2014a,b), Li et al. (2016)). Similar algorithms have been tested for a dynamical system (see Duriez et al. (2016)) to find the optimal feedback controller with respect to the objective $\mathcal{J}$.

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