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# Interactions between two flat plates at different positions in a current

D. Yang [a], B. Pettersen [b], Y.L. Xiong [c,d,*]

[a] School of Naval Architecture and Ocean Engineering, Huazhong University of Science and Technology (HUST), Wuhan 430074, China
[b] Department of Marine Technology, Norwegian University of Science and Technology (NTNU), Trondheim NO-7491, Norway
[c] School of Civil Engineering and Mechanics, Huazhong University of Science and Technology (HUST), Wuhan 430074, China
[d] Hubei Key Laboratory of Engineering Structural Analysis and Safety Assessment, Luoyu Road 1037, Wuhan 430074, China

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ABSTRACT

Two-dimensional flow over two inclined flat plates in a staggered arrangement at low Reynolds numbers has been investigated by numerical simulation. The two flat plates with the same length $d$ and thickness are modeled using the immersed boundary method. The spacing between the centers of the two plates in streamwise and transverse direction is in the range of $s/d \leq 6.0$ and $t/d \leq 0.8$, respectively, with one plate always located in the wake interference area of the other plate. The lift, drag, and moment coefficients are investigated systematically based on the variation of the spacing and the inclination angles of the two plates. The frequency domain was obtained through fast Fourier transform of the velocity component. The results show that, for cases with $s/d < 2.5$, both of the plates are suffering significant effect due to the existing of the other plate. The drag and lift forces on the upstream plate decrease with 17% and 20%, while the drag and lift forces on the downstream plate decrease with 52% and 66%. For cases with $s/d > 2.5$, the interaction to the upstream plate is smaller compared to the downstream plate, and new frequencies are exited in the wake of the second plate.



## 1. Introduction

Flow around two or more bluff bodies close to each other involves not only the complex wake pattern behind them, but also fluid interaction effects between the bodies. There are several situations occurring such as separation, vortex shedding and wake interference involving bodies like bridge piers, buildings, dragonfly wings, chimneys, pipelines, rack of marine risers, cooling of electronic components and bubbles in multi-phase flow. Flow past an inclined flat plate which represents high-lift bluff body flows, has been proven to be a good choice for representing similar flow features of both airfoil and hydrofoil (Breuer and Jovičić, 2001; Breuer et al., 2003). The wake interference behind two inclined flat plates which could be applied in aerodynamic and hydrodynamic problems, corresponding to dragon flight (Zhang and Lu, 2009), multiple rudders (Tabaczek and Kulczyk, 1997; Gim, 2013), tidal sails (Cebrian et al., 2013), and so on, possess rich physical and practical information.

Compared to the flow past a circular cylinder, which has been studied most extensively among other body shapes in both experimental and numerical studies, the flow past a flat plate with different inclination angles ($\alpha$) is characterized by fixed separation points at the edges of the plate. The wake behind an inclined flat plate possesses an asymmetrical time-averaged mean pattern while the instantaneous flow is dominated by periodic coherent patterns due to the vortex shedding. The experimental studies of Lam (1996) and Lam and Leung (2005) show that the train of trailing edge vortices has higher vortex strength than the train of leading edge vortices. Knisely (1990) measured Strouhal numbers for a family of rectangular cylinders with side ratios ranging from 0.04 to 1.0 and with angles of attack from 0° to 90°, it was found that the Strouhal number, defined by vortex shedding frequency, $f$, scales with the projected width $B'$ of the plate normal to the free-stream, is approximately constant at $St' = fB'/U_\infty \approx 0.15$ for $\alpha = 30$–90°, with $U_\infty$ being the free-stream velocity.

The present study is going to investigate the flow past two inclined flat plates. However, there are an infinite number of possible arrangement of the two plates, here we adopt a simple classification by Zdravkovich (1977) for flow past two circular cylinders, where the configuration is classified into three arrangements: tandem, side-by-side, and staggered. Due to the complexity and expensive cost in three-dimensional computations, in the present paper, two-dimensional calculations are performed with two inclined flat plates in tandem and staggered configurations. The two-dimensional simulation for a single plate is carried out as well and compared with the three-dimensional DNS simulation results (Yang et al., 2012).

* Corresponding author at: Hubei Key Laboratory of Engineering Structural Analysis and Safety Assessment, Luoyu Road 1037, Wuhan 430074, China. Tel.: +86 180 6240 2239.
*E-mail address:* xylcfd@hust.edu.cn (Y.L. Xiong).

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**Nomenclature**

| | |
|---|---|
| $\alpha$ | Angle of attack |
| $\alpha_1$ | Upstream plate attack angle |
| $\alpha_2$ | Downstream plate attack angle |
| $\nu$ | Kinematic viscosity |
| $\rho$ | Density of water |
| $C_L$ | Lift coefficient |
| $C_D$ | Drag coefficient |
| $C_M$ | Moment coefficient |
| $d$ | Plate length |
| $d_1$ | Upstream plate length |
| $d_2$ | Downstream plate length |
| $f_1$ | Primary frequency |
| $f_2$ | Secondary frequency |
| $f_3$ | Tertiary frequency |
| $F_L$ | Lift force |
| $F_D$ | Drag force |
| $M$ | Moment |
| $\hat{p}$ | Non-dimensional pressure |
| $Re$ | Reynolds number |
| $s$ | Streamwise spacing of plates |
| $St$ | Strouhal number |
| $t$ | Transverse spacing of plates |
| $\hat{t}$ | Non-dimensional time |
| $T_1$ | Primary period |
| $\hat{u}$ | Non-dimensional streamwise velocity |
| $\hat{v}$ | Non-dimensional transverse velocity |
| $U_0$ | Free-stream velocity |

The motivation of the present paper is to investigate the wake interference to reveal the dynamic mechanisms for both of the plates. The flow characteristics due to the existence of the upstream bluff body result in a fluctuating flow field and thus drag and lift forces acting on both of the bodies. As Zdravkovich (1977) suggested, the forces acting on the body should be used as criterion for the classification of staggered arrangement for two circular cylinders. In this paper we will adopt the time-averaged drag and lift forces of one single flat plate to verify the force variations of two plates in different configurations.

## 2. Methodology and numerical Validation

We consider incompressible fluid with free-stream velocity $U_0$ in $x$-direction past two inclined flat plates of chord length $d_1 = d_2 = d$ and thickness $0.02d$, as shown in Fig. 1. The control parameters are the streamwise $s/d$ and transverse $t/d$ spacing ratio between the plate centers, and the inclined angle $\alpha_1$ and $\alpha_2$ for the two plates, respectively. The Reynolds number is defined as $Re = U_0 d/\nu$ with $\nu$ as the kinematic viscosity of the fluid.

Here, the systematical study is carried out for $0 \le s/d \le 6.0$, $0 \le t/d \le 0.8$, and $0 \le \alpha_1, \alpha_2 \le 25^\circ$. For $\alpha = 25^\circ$, it has been proved that the three-dimensional effects appear between $Re = 275$ and $Re = 300$ (Yang et al., 2012). Therefore the staggered arrangements are carried out at $Re = 200$ to investigate the drag and lift coefficients on both plates. From the two-dimensional study of Zhang et al. (2009), they found that the flow experience the successive period-doubling and various incommensurate bifurcation to chaos as the Reynolds number increase at $\alpha = 25^\circ$. The nonchaotic flow persists up to $Re = 730$. To investigate the Strouhal number variation, the tandem arrangements are chosen at certain Reynolds number range, at which the flows have not reached the chaos state. The Reynolds numbers simulated are not exactly the same for all cases, since the wake behind the upstream plate could be

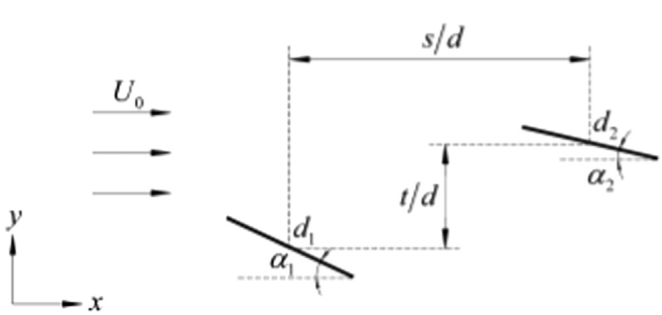


**Fig. 1.** Sketch of the relative arrangement of the two plates.

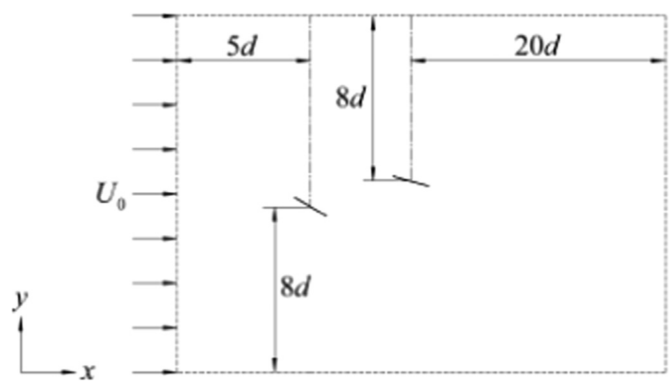


**Fig. 2.** Sketch of the computational domain (horizontal length $(25d + s)$, and vertical length $(16d + t)$).

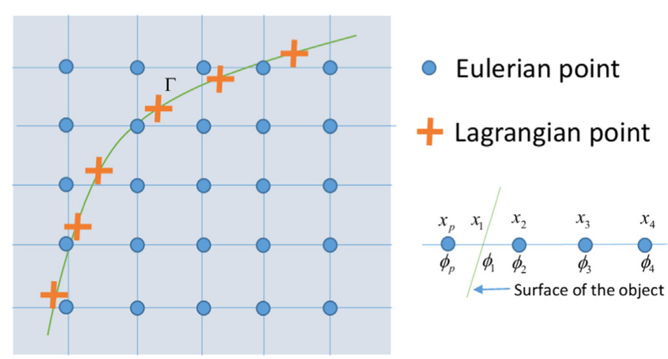


**Fig. 3.** Eulerian point and Lagrangian point in IBM and the determination of boundary.

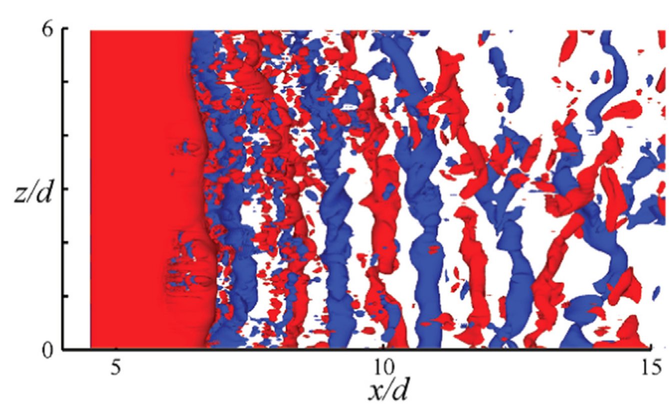


**Fig. 4.** An iso-surface of the spanwise vorticity component at $Re = 1000$ and $\alpha = 20^\circ$.