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Vortex dynamics in a wire-disturbed cylinder wake

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The effect of a thin control wire on the wake properties of the flow around a circular cylinder has been investigated numerically. The governing equations are solved using a spectral element method for a Reynolds number of $Re_D=100$. The diameter ratio of the main cylinder and the wire equals $D/d=50$ so no vortex shedding is expected to occur for the wire. However, the vorticity introduced by the wire in the vicinity of the upper shear layer of the cylinder still affects the vortex dynamics in the wake of the main cylinder. The primary effect of the wire is the reduction of the velocity fluctuations in the vortex formation region of the main cylinder. The maximum decrement occurs at a wire position of $y_w/D=0.875$. The secondary effect of the wire is observed in the kinematics of the vortices, leading to a modified vortex arrangement and strength difference between the upper and lower vortices. Due to these effects, for $y_w/D \leq 0.875$, a downward wake deflection is observed, while for larger values of $y_w/D > 0.875$, an upward deflection is found. The maximum downward deflection occurs at wire position $y_w/D=0.75$ where the maximum positive mean lift coefficient, minimum drag coefficient, and minimum fluctuating lift coefficient are seen. Based on the observations, it is concluded that the deflection of the wake is primarily caused by a modification of the vortex arrangement in the wake. This modified vortex arrangement is caused by different formation times of the upper and lower vortices, by different vortex strengths, or by both. © 2010 American Institute of Physics. [doi:10.1063/1.3466659]

I. INTRODUCTION

Knowledge of bluff body wake flows has a great importance for many daily life applications. Therefore, bluff body wake flows have become a favorite issue for research in decades. Due to its simple geometry, the flow around circular cylinders has become a central topic in these researches. One of the first studies on the stability of cylinder wake flows was performed by von Kármán at the beginning of the 20th century. He modeled the wake using point vortex approach and determined the necessary criterion for the stability of the wake. von Kármán's approach was discussed in detail by Lamb.¹ Roshko^{2,3} performed extensive experimental studies on cylinder wakes using hot-wire anemometry. He measured the shedding frequencies at a wide range of Reynolds numbers and suggested a universal relation between the Reynolds number and the shedding frequency. Moreover, a lot of effort was made to explain the physics of circular cylinder wake dynamics. The physical mechanism of vortex shedding is discussed in the works of Gerrard⁴ and Green and Gerrard.⁵ They showed that vortex shedding for low Reynolds numbers can be characterized by vortex splitting and high shear stress occurring in the near wake. However, their study was limited to the two-dimensional aspects of the flow. The three-dimensional aspects of wake flows behind circular cylinders are thoroughly reviewed and discussed by Williamson.^{6,7} He grouped the circular cylinder flow into various regimes according to the Reynolds number. The laminar vortex shedding regime extends from a Reynolds number of 49 to 140–

194. According to his grouping, the flow regime between $Re=190$ and 260 was denoted as the three-dimensional wake transition regime. This regime was associated with two modes of shedding, modes A and B.

Parallel to the studies of single cylinder flow, many researchers have conducted flow control studies. The importance of flow control studies comes from the need to reduce drag and vibration of bluff bodies. The most recent review on flow control studies can be found in Ref. 8. The authors grouped the methods for three-dimensional forcing of two-dimensional bodies into two categories; active control methods and passive control methods. Passive control methods involve techniques that modify the geometry and configuration. One of the most simple passive control techniques is placing a small secondary control cylinder in the wake of the main bluff body. There are several researches that focused on the physical mechanisms of the cylinder-control cylinder interactions.

The mechanism of flow suppression by using an external control cylinder was explained by Strykowski and Sreenivasan.⁹ They performed experiments at different Reynolds numbers with different sizes and positions of the control cylinder. In their investigation, they found that the major effect of placing a control cylinder is damping the velocity fluctuations. Moreover, they discussed that for small Reynolds numbers, there exists a region in which the control wire can be placed for maximum effectiveness in damping and vortex shedding suppression. They also reported that this region is in the near wake of the cylinder, outside the maximum vorticity line of the steady wake and its shape depends on the Reynolds number of the main cylinder flow and the

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diameter ratio. Furthermore, they did not achieve a suppression for $Re > 80$. However, the shedding frequency was reduced considerably for that particular case. They concluded their experiments with an explanation of the suppression mechanism using the approach of interacting shear layers as introduced by Gerrard.⁴ By placing the control cylinder in the near wake, the concentrated vorticity diffuses such that the attraction force between the opposing shear layers decreases. This reduction results in a lower shedding frequency.

Mittal and Raghuvanshi¹⁰ studied cylinder-wire interaction using finite element methods for different Reynolds numbers: $Re = 60, 70, 80, 100$. They used the same diameter ratio of $D/d = 7$ as Strykowski and Sreenivasan.⁹ They showed that vortex shedding is completely suppressed for certain positions of the wire at low Reynolds numbers. The mechanism of control was explained by comparing the downstream variation of pressure in the upper shear layer and in the wake. Their conclusion about the shedding suppression was that the control cylinder provides a local favorable pressure gradient that stabilizes the shear layer locally. The magnitude of this favorable pressure gradient determined the extent to which the shear layer was stabilized.

The configuration was further studied by Dipankar *et al.*¹¹ They used an energy-based receptivity method to evaluate the effect of the control cylinder on the vortex shedding mechanism. The results were also postprocessed by using proper orthogonal decomposition. They achieved suppression and drag for all the simulated cases. In their study, the control cylinders led to the suppression of the wake oscillations and to a longer formation length with a narrow wake width. They reported that the diffusive effect of the wire is different for different Reynolds numbers as the effect of shear coming from the main cylinder toward the control cylinder is different. They concluded that the control cylinder acts like a disturbance energy sink affecting the normal cycle of vortex shedding.

The results of Strykowski and Sreenivasan⁹ about wake control were also evaluated by a sensitivity analysis of Marquet *et al.*¹² The sensitivity analysis was applied to the vortex shedding behind a circular cylinder for Reynolds numbers of $47 \leq Re \leq 80$. The authors showed that when the control cylinder is placed at its optimal position, the production of perturbations in the rear of the symmetrical recirculation region is damped and the flow is stabilized.

In addition to the single control cylinder configuration, Kuo *et al.*¹³ studied the configuration with two symmetrically placed control cylinders at $(x/D, y/D) = (0.5, \pm 0.6)$. They reported that the form drag of the main cylinder can be reduced significantly for increasing Reynolds number. However, they did not achieve any shedding suppression for the investigated situations.

In addition to the two-dimensional flow studies that were summarized above, Zhang *et al.*¹⁴ studied the effect of a control wire close to the cylinder in the transition regime. In their study, they performed experiments and numerical simulations to evaluate the effect of the wire. They concluded that the presence of a wire in the near wake of the cylinder triggers a new mode of vortex shedding with different length scales compared to the other shedding modes, mode A and

mode B. Therefore, they introduced a new mode of transition, that is, mode C transition. The authors showed that mode C structures have a spanwise wavelength of approximately 1.8 cylinder diameter and appear at Reynolds number ranges of 170–270.

Several studies concentrated on the control and analysis of high Reynolds number flows. Sakamoto and Haniu¹⁵ performed wind tunnel experiments at the Reynolds number of 65 000 and diameter ratio of approximately 18. Their study concentrated on the effect of the control cylinder on fluid forces and shedding frequencies by placing the control cylinder very close to the main cylinder. They reported that the displacement of the separation point on the surface of the main cylinder results in large reductions in the time averaged drag. Dalton *et al.*¹⁶ used flow visualization studies in addition to numerical simulations to study the suppression of vortex shedding at moderate Reynolds numbers. They noted that the minimum values for drag and lift coefficients depend on the gap ratio between the two cylinders and the angle of attack of the main flow.

In all cases mentioned above, the wake was modified by placing a control cylinder in the near wake of the main circular cylinder. Another method of wake distortion is heating the main cylinder. The behavior of the disturbed wake for the heated cylinder case was studied by Kieft *et al.*¹⁷ by means of particle tracking velocimetry. In their experiments, they observed a downward deflection of the wake. Then, the authors used point vortex model for explaining the trajectories of the individual vortices and wake deflection. The downward deflection phenomenon was later evaluated by Kieft *et al.*¹⁸ using spectral element method (SEM) simulations. In both of the works, the authors' conclusion was that the vortices in the upper and lower rows have different strengths because of the heat added from the surface of the cylinder and this strength difference caused a downward deflection of the wake by inducing different convection velocities for the upper and lower vortex rows.

The aforementioned studies on the effect of a control cylinder all focus on the near-wake dynamics such as vortex formation mechanisms, drag, and shedding characteristics. However, little attention has been paid to the dynamics and properties of the shed vortices in the far wake. Ahlborn *et al.*¹⁹ used empirical methods to derive relations between the drag, shedding frequency, and some properties of the wake of a single cylinder. However, their study did not include any discussion about the wake trajectories. First, they analyzed the well-known trends of $St-Re$ relationship and explained the discrepancies between different analytical models using vorticity diffusion parameter. Second, they derived several relationships for the estimation of wake parameters from measured Strouhal numbers and drag coefficients. Third, they related the universal Strouhal number to the geometric values of the wake.

Visualization experiments in our laboratory on wire-disturbed three-dimensional transition of the flow around a cylinder using tin-precipitation method in the towing tank showed that the presence of a wire modifies the vortex dynamics and trajectories. The details of the method can be found in Ref. 20. Sample images from these preliminary ex-

FIG. 1. (Color online) Flow visualization images of wire-disturbed circular cylinder wake [$Re_D=100$, $x_w/D=0.75$].

periments are shown in Fig. 1, where a downward tendency of the wake axis for the $x_w/D=0.75$ case and an upward tendency for the $x_w/D=1.0$ case are observed. The top figure shows the visualization result for the nonwired case. A regular staggered pattern of the shed vortices is observed. For $y_w/D=0.75$ case, the upper vortex row is shifted downward. This also seems to hold for the lower vortex row although to a lesser extent. For $y_w/D=1.0$ case, the whole vortex street seems to show a widening where the upper vortices are shifted upward and the lower vortices downward. Because the upward motion appears to be larger than the downward one, the wake axis moves up. This phenomenon has not been mentioned before and is the topic of this paper.

Hence, the present paper mainly focuses on the wake deflection phenomenon, i.e., kinematics of the vortices in the wire-disturbed circular cylinder wake flow for a Reynolds number of $Re=100$ as function of various wire positions. The secondary aim is to evaluate the influence of different positions of a very small wire on the characteristics of the main cylinder, such as lift and drag coefficients, shedding frequency, etc.

The plan of this paper is as follows. The definition of the problem, the details of configuration, and the solution methodology are described in Sec. II. In Sec. III, the results of spectral element simulations are shown. Besides, point vortex simulation results that are used for further discussion of the wake deflection are presented. Finally, Sec. IV contains the discussion of the results on the wake deflection phenomenon and some concluding remarks.

II. METHODOLOGY

A. Problem definition and configuration

The configuration that has been studied consists of two circular cylinders with diameters D and d , respectively (Fig. 2). The corresponding diameter ratio is $D/d=50$. Since this value is quite large, the smaller cylinder can be thought of as a wire and will be denoted as such throughout the text. As presented in Fig. 2, the free-stream velocity U_∞ is in the $+X$

FIG. 2. Description of cylinder-wire configuration and notation.

direction, while the $+Y$ direction is upward. The Reynolds number $Re_D=DU_\infty/\nu$ for the main cylinder equals $Re_D=100$ and is fixed throughout this study. Therefore, the flow around is isolated from three-dimensional effects, i.e., vortex dislocations and mode A structures, and can be considered as two-dimensional.⁷ Considering the diameter ratio between the cylinder and the wire, it should be noted that the Reynolds number for the wire is $Re_d=2$. This indicates that no vortex shedding occurs from the wire itself.

The position of the wire is determined in a Cartesian coordinate system, the origin of which is at the center of the main cylinder. x_w/D and y_w/D represent the nondimensional position of the wire with respect to the center of the cylinder. The horizontal position of the wire was fixed at $x_w/D=0.75$ but the vertical position changes from $y_w/D=0.5$ to $y_w/D=2.0$ in the present study. The simulation matrix for the cases presented in the present study is summarized in Table I.

B. Numerical simulations

The solution of the flow problem is achieved by solving the governing equations for two-dimensional and incompressible viscous flow in nondimensional form,

$$\nabla \cdot \mathbf{u} = 0, \quad (1)$$

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} = -\nabla p + \frac{1}{Re} \nabla^2 \mathbf{u}. \quad (2)$$

Here, the velocity is scaled by using the free-stream velocity U_∞ , length by using the cylinder diameter D , time variable by D/U_∞ , and pressure term by ρU_∞^2 . $\mathbf{u}=(u,v)$ is the dimensionless velocity field.

TABLE I. Simulation matrix for the present study.

	Re_D	x_w/D	y_w/D
Case 1	100	<i>No wire</i>	
Case 2	100	0.75	0.5
Case 3	100	0.75	0.625
Case 4	100	0.75	0.75
Case 5	100	0.75	0.875
Case 6	100	0.75	1.0
Case 7	100	0.75	1.5
Case 8	100	0.75	2.0

FIG. 3. Domain and grid properties for case 4. (a) Quadrilateral elements, domain size, and boundary locations of the whole domain for single cylinder simulations. (b) Quadrilateral grid elements and the calculation points between the cylinder and the wire. The solution in each element is approximated with sixth-order polynomial.

The numerical simulations of the flow are carried out by solving Eqs. (1) and (2). A high-order spectral element method is employed for the spatial discretization of the problem. As shown in Fig. 3(a), the calculation domain has dimensions of $60D \times 48D$. The domain is decomposed into 752 quadrilateral elements for the nonwired case and 982 for the wired cases. For each element, the solution is approximated by using sixth-order polynomial expansion. Thus, within each element, there are 7×7 calculation points. The nondimensional time steps of 0.03 and 0.004 are used for nonwired and wired cases, respectively. These time steps correspond to a Courant number of approximately 0.3 for both cases. In addition, special care was taken of the elements bordering the surface of both the main cylinder and the wire in order to represent the geometry accurately. Especially, the grid around the wire had to be fine enough to resolve the shear layers around it [see Fig. 3(b)].

The unsteady Navier–Stokes equations are solved using an operator splitting approach in combination with a pressure correction method. In this solution technique, velocity and pressure terms are decoupled, yielding a convection-diffusion problem for the velocity terms u and v and a Poisson equation for the pressure related correction term p^* . This solution procedure was proposed and implemented by Timmermans *et al.*²¹ and used by Kieft *et al.*¹⁸ and Ren *et al.*²² in their simulations. The prescribed boundary conditions are shown in Fig. 3(a) and summarized in Table II. The use of a

TABLE II. Boundary conditions for the calculation domain. u and v denote, respectively, the horizontal and vertical velocity components and p^* is the pressure related correction term. $\partial/\partial n$ denotes the normal derivative.

Inflow	$u=1$	$v=0$	$\partial p^*/\partial n=0$
Outflow	$\partial u/\partial n=0$	$\partial v/\partial n=0$	$p^*=0$
Upper and lower	$\partial u/\partial n=0$	$v=0$	$\partial p^*/\partial n=0$
Cylinder and wire	$u=0$	$v=0$	$\partial p^*/\partial n=0$

pressure correction scheme requires the use of homogeneous Neumann boundary conditions for p^* except for the outflow where the use of stress-free boundary conditions for the velocity imposes $p^*=0$.

Validation of the simulation method is checked by comparing the nondimensional shedding frequency obtained with values in literature.^{10,23,24} The comparison has been performed for the shedding frequency of the nonwired single cylinder flow for $Re_D=100$. In Table III the values from different references are compared. From the table, it is seen that the results obtained are consistent with the results from the literature.

C. Data processing

For the data presentation and other postprocessing purposes, the velocity gradients are calculated using the spectral interpolation functions that are used for the solution of the governing equations. Lift and drag coefficients of the main cylinder are calculated by integration of the stress vector over the surface of the cylinder.

Vortices are defined using the λ_2 -method. The λ_2 -value as defined in Eq. (3) is actually the discriminant of the non-real eigenvalues of the velocity gradient tensor. It is shown that regions with negative values of λ_2 indicate the presence of vortical structures,^{25,26}

$$\lambda_2 = \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right)^2 - 4 \left(\frac{\partial u}{\partial x} \frac{\partial v}{\partial y} - \frac{\partial u}{\partial y} \frac{\partial v}{\partial x} \right). \quad (3)$$

Therefore, a vortex is defined as a region that is bounded with a closed λ_2 contour line. Although the numerical value that defines the contour level is free to choose, in this analysis, the value is set to be -0.1 . So, any closed contour region where $\lambda_2 \leq -0.1$ is defined as a vortex.

TABLE III. Comparison of Strouhal numbers for flow past a circular cylinder for Reynolds number of $Re_D=100$.

Reference	Method	Strouhal number, $St=f_{shed}D/U_\infty$
Williamson ^a	Experimental	0.165
Williamson and Brown ^b	Experimental, curve fit	
	$St=0.2665-1.018/\sqrt{Re}$	0.165
Mittal and Raghuvanshi ^c	Numerical	0.168
Present study	Numerical	0.166

^aReference 23.

^bReference 24.

^cReference 10.

The circulation, i.e., strength, of a vortex is given by the area integral,

$$\Gamma = \int_A \omega_z dA, \quad (4)$$

where the area A is enclosed by the contour $\lambda_2 = -0.1$. An unstructured triangular grid within a vortex area is used to perform the numerical integration. The position of a vortex is determined by the location of its center, which is calculated as

$$x_c = \frac{1}{\Gamma} \int_A \omega_z x dA, \quad (5)$$

$$y_c = \frac{1}{\Gamma} \int_A \omega_z y dA. \quad (6)$$

Trajectories are extracted by tracking the vortex centers after formation. Each trajectory was plotted by tracking one single vortex from formation until its exit of the calculation domain. Two vortices were tracked individually for each case, i.e., one from the upper row and one from the lower row. The wake orientation was then calculated by taking the mean of upper and lower vortex trajectories.

The effect of a wire on the vortex formation is also assessed by defining two additional parameters: local period averaged vorticity flux and total period averaged vorticity flux (see Sec. III D). The local period averaged vorticity flux is defined as the flux of vorticity at cross stream line $x/D = 1$ and is formulated as

$$\langle \phi_{\omega_z}(y) \rangle = \frac{1}{T_{\text{shed}}} \int_{T_{\text{shed}}} u(y) \omega_z(y) dt, \quad (7)$$

where T_{shed} is the shedding period. The spatial integration of $\langle \phi_{\omega_z} \rangle$ over the cross section $x/D = 1$ gives the total period averaged vorticity flux Φ , which is a measure of all upstream produced vorticity that possibly ends up in the vortex structures. For the upper half of the wake, the integration domain is taken as $y = [0, L]$. The total period averaged vorticity flux Φ_U then becomes

$$\Phi_U = \frac{1}{L} \int_0^L \langle \phi_{\omega_z}(y) \rangle dy. \quad (8)$$

Similarly, for the lower half of the wake, the total period averaged vorticity flux Φ_L is based on the integration domain $y = [-L, 0]$.

D. Point vortex model

The interaction of different vortices in the circular cylinder wake determines the behavior of the wake as a whole. A simple approach to model these interactions is the point vortex model. The vortex arrangement and configuration of the point vortex model are shown in Fig. 4. In this model, every single vortex located at (x_j, y_j) in the wake is assumed to be a point vortex with a strength of Γ_j . The vortices are assumed to be away from the formation region. The velocity of a point vortex at the location (x_j, y_j) is equal to the sum-

FIG. 4. Point vortex model used for the analysis of the wake behind the inflow region.

mation of velocities induced by other vortices.²⁷ This formulation under a constant horizontal free-stream velocity U_∞ takes the form

$$u_j = U_\infty - \frac{1}{2\pi} \sum_{i \neq j} \frac{\Gamma_i (y_j - y_i)}{(x_i - x_j)^2 + (y_i - y_j)^2}, \quad (9)$$

$$v_j = \frac{1}{2\pi} \sum_{i \neq j} \frac{\Gamma_i (x_j - x_i)}{(x_i - x_j)^2 + (y_i - y_j)^2}. \quad (10)$$

The derivation of the point vortex equations is made under the assumption of infinitely long vortex rows. Due to the finite size of the calculation domain in this research, the vortex rows are of finite length. This situation creates fluctuations in the trajectories at both ends of the calculation domain. In order to overcome this problem, an inflow region is defined. This region has a constant number of vortices that are positioned according to the stability criterion $a/\delta_1 = 0.281$ of von Kármán. The vortices in the inflow region are allowed to move only in x -direction with the velocity of $u = U_\infty - \Gamma/(\delta_1 \sqrt{8})$. As soon as a vortex leaves the inflow region, all the restrictions on its position and motion are removed.

The relative position of vortices with respect to each other is determined by the spacing ratio of δ_1/δ_2 . The ratio δ_1/δ_2 for a specific upper vortex is defined as the distance to the previously shed upper vortex divided by the distance to the previously shed lower vortex (see Fig. 4).

III. RESULTS

A. Time-averaged streamwise velocity fluctuations

Numerical results of the time averaged streamwise velocity fluctuations $\langle u_{\text{rms}} \rangle$ for various wired and nonwired cases are shown in Fig. 5. The “no-wire” case represents the single cylinder flow without the effect of the wire in the near wake. Detailed observation of Fig. 5 reveals that placing a wire at one side of the cylinder has two consequences for the $\langle u_{\text{rms}} \rangle$ results; the fluctuation levels and the symmetry of the fluctuation contours change.

For the wire locations of $y_w/D = 0.75, 0.875$, and 1.0 , the differences from the reference nonwired case are clearly noticeable. It is evident from the contour levels for the cases $y_w/D = 0.75, 0.875$, and 1.0 that the level of horizontal velocity fluctuations is reduced. These observations are quantified by probing the maximum values of the time averaged horizontal velocity fluctuations in the wake for each case (see Table IV). The negative values for the difference indicate a

FIG. 5. Time-averaged streamwise velocity fluctuations $\langle u_{rms} \rangle$ contours obtained from SEM simulations [$Re_D = 100$, $x_w/D = 0.75$].

reduction of velocity fluctuations. The velocity fluctuation levels are reduced in all cases. However, for the cases $y_w/D = 0.75, 0.875$, and 1.0 , the damping is larger than 10% with $y_w/D = 0.875$ having a maximum of 15.29%. For the rest of the wire positions, the damping is of the order of a few percent. All the three wire positions with high damping values are above the maximum vorticity line of the nonwired cylinder wake, as shown in Fig. 6, where the wire positions are superposed with the time mean vorticity field of the nonwired cylinder wake. It is likely that the wire-induced vorticity is diffused in the upper shear layer of the main cylinder due to the interaction of the wire-generated positive vorticity and cylinder generated negative vorticity for these three wire positions. The trend in the fluctuation difference with respect to the wire position in Table IV indicates that there is an optimal position for the wire where the highest damping of

TABLE IV. Maximum levels of velocity fluctuations $\langle u_{rms} \rangle$ obtained from SEM simulations. The last column shows the difference with respect to the reference single cylinder case. The negative values indicate reduction in fluctuation levels.

Wire position	$\langle u_{rms} \rangle _{max}$	Difference (%)
No wire	0.3205	
$y_w/D = 0.5$	0.3174	-0.97
$y_w/D = 0.625$	0.3046	-4.96
$y_w/D = 0.75$	0.2844	-11.26
$y_w/D = 0.875$	0.2715	-15.29
$y_w/D = 1.0$	0.2826	-11.83
$y_w/D = 1.5$	0.3181	-0.75
$y_w/D = 2.0$	0.3182	-0.75

FIG. 6. Positions of the wire in the time mean vorticity field of the nonwired cylinder flow. The contours represent the mean vorticity in the upper shear layer, while the solid line is the maximum vorticity line, i.e., centerline for the upper shear layer [$Re_D=100$, $x_w/D=0.75$].

the velocity fluctuations is achieved. This optimal position is $y_w/D=0.875$ in the present study and above the maximum vorticity line, which is consistent with the conclusions of Strzykowski and Sreenivasan.⁹

Another effect of the wire is breaking the symmetry in the $\langle u_{rms} \rangle$ contour plots. In the reference nonwired case, the $\langle u_{rms} \rangle$ contours are perfectly symmetric with respect to the wake center line $y/D=0$. However, when Fig. 5 is examined in detail, it can be seen that for all other cases, the symmetry is broken. This effect of breaking the symmetry is most pronounced for the cases of $y_w/D=0.875$ and 1.0. For the $y_w/D=0.875$ situation, the fluctuation contours in the lower part of the wake are elongated and its maximum point is closer to the cylinder than the maximum point in the upper part. For the $y_w/D=0.75$ case, the elongated contours are located in the upper part of the wake and the maximum points in the upper and lower parts are located nearly at the same downstream position. These asymmetries in the $\langle u_{rms} \rangle$ fields suggest that there might be a difference in the formation process of the upper and lower vortices.

B. Shedding frequency

The shedding frequency of the vortices is represented by the Strouhal number, which is defined as $St = f_{shed} D / U_\infty$. The vortex shedding frequencies and the corresponding Strouhal numbers are extracted from the calculated horizontal velocity data obtained by data probing at the position $(x/D, y/D) = (2, 0)$. The values of the Strouhal numbers for different wire positions are presented in Fig. 7. As shown previously in Table III, the Strouhal number for the nonwired case is calculated to be $St=0.166$. This value is indicated as a dashed line in Fig. 7. Placing the wire at a position of $y_w/D=0.5$ does not change the shedding frequency. This is in line with the former results for the velocity fluctuations, where for this case a very small reduction was observed. The Strouhal number takes its minimum value when the wire is placed at the position of $y_w/D=0.875$. This corresponds to a shedding frequency reduction of 9.64% compared to the non-

FIG. 7. Nondimensional shedding frequency, St as a function of the vertical position, y_w/D [$Re_D=100$, $x_w/D=0.75$].

wired case. One can recall from Table IV that this wire position is the one where maximum damping of the velocity fluctuations is found. From that position on, the shedding frequency rises again up to the value for the nonwired case.

In order to determine the effect of the streamwise coordinate of the wire, simulations were also performed at the vertical position of $y_w/D=0.875$, for which shedding frequency of the main cylinder was found to be most affected. It was found that the effect of the horizontal position has a minor effect on the shedding frequency when compared to the effect of the vertical position. In Ref. 9, it was shown that the optimum position of the second cylinder for the wake control lies within boundaries of a closed elliptical region that is stretched in streamwise direction and this region shrinks to a very small area for high D/d ratios at a certain Reynolds number. From their conclusions, it can also be understood that the shedding frequency of the main cylinder is more sensitive to the vertical position of the control cylinder than for the horizontal position for a specific configuration. Therefore, the wake dynamics analysis is only performed and reported for the horizontal wire position of $x_w/D=0.75$.

C. Wake behavior

The vorticity field, vortex boundaries defined by constant λ_2 value, and trajectories of the vortices for the wire positions of $y_w/D=0.75, 1.0, 2.0$ are shown in Fig. 8. The figure represents the instants at which the upper vortices are formed. The downward deflection of the wake is noticeable for $y_w/D=0.75$ in Fig. 8(a). However, the tendency of the wake is upward in Figs. 8(b) and 8(c) in which the wire is positioned at $y_w/D=1.0$ and $y_w/D=2.0$, respectively. Moreover, the interaction of the wire-generated vorticity in the upper vortex formation area is seen in Figs. 8(a) and 8(b) where the wire is positioned in or close to the upper shear layer. For the $y_w/D=2.0$ situation, the wire is clearly out of the shear layer and does not show any vortex shedding.

In order to elucidate the effect of the wire on the cylinder wake behavior, it is necessary to look into the trajectories and strengths of the vortices for the simulated cases. The simulated cases are categorized into three groups according to the tendency of trajectories. In order to be remote of the

FIG. 8. Flow field characteristics for the sample cases obtained from SEM simulations. Contour plot indicates the vorticity field; solid lines are $\lambda_2 = -0.1$ contour lines and dashed lines represent the vortex trajectories for the upper and lower vortex rows [$Re_D = 100$, $x_w/D = 0.75$].

formation dynamics region and the numerical influences of the outflow boundary, the trajectories are plotted for the domain $8 \leq x/D \leq 32$.

The results for the first group are presented in Fig. 9. In the cases $y_w/D = 0.5$ and 0.625 , the vortices follow almost the same trajectories with a minor downward deflection when compared to the single cylinder case. Figure 9(a) shows the vortex trajectories. The deflection is so low that it can be accepted as there is no wake deflection at all for the aforementioned cases. This is also evident from Fig. 9(b) where the wake centerlines are shown. The comparison of the vortex strengths also shows that there is no apparent strength difference between the considered cases and the reference no-wire case [see Fig. 9(c)]. After these observations, one may conclude that placing the wire at the positions of $y_w/D = 0.5$ and 0.625 does not bring any significant difference by means of vortex trajectories and vortex strengths. However, as stated in the previous section, the velocity fluctuations and the Strouhal numbers are reduced.

The second group contains the cases with wire position $y_w/D = 0.75$ and 0.875 in which the wake tendency is downward. The wake properties of these two cases are shown in Fig. 10. Examining the trajectories in Fig. 10(a) shows that there is a uniform downward shift of both upper and lower vortex trajectories for the $y_w/D = 0.75$ case. On the other hand, the trajectories for the $y_w/D = 0.875$ case are not as uniform as for the $y_w/D = 0.75$ case. Despite the downward tendencies of both wakes, it is seen that they show different

behaviors when the wake centerline curves for both cases are compared. As shown in Fig. 10(b), the wake centerline shows a linear downward path for the $y_w/D = 0.75$ case. On the other hand, the upward tendency of the upper vortices for $x/D > 17$ in Fig. 10(a) is because of the widening of the vortex street that is also seen in the no-wire case. On the contrary, the wake for the $y_w/D = 0.875$ case shows different characteristics throughout the domain of interest. First, the upper row shows higher upward deflection for downstream positions of $x/D > 17$. Second, the lower vortices are constantly moving downward with decreasing vertical velocity. This results in a convex trajectory. The combination of these two differences ends in a parabolalike wake centerline curve with a minimum vertical position around $x/D \approx 19$ [see Fig. 10(b)]. Therefore, the upward trajectory of the upper vortex row cannot be solely because of vortex street widening. When the strengths of these vortices are compared, one can see that both the upper and lower vortices in the $y_w/D = 0.75$ case have almost the same strength as the reference nonwired case, as shown in Fig. 10(c). On the other hand, the upper vortices for $y_w/D = 0.875$ case are weaker and the lower vortices are stronger than their counterparts in the non-wired case. A downward deflection of the vortex street can be caused by a strength difference between the upper and lower vortex rows, as observed for the heated cylinder case in Ref. 18. This possibly explains the downward deflection for the $y_w/D = 0.875$ case. However, such a strength differ-

FIG. 9. Wake properties obtained from SEM simulations at the wire positions of $y_w/D=0.5$ and $y_w/D=0.625$ for $Re=100$. (a) Vortex trajectories, (b) wake centerlines, and (c) vortex strengths [$Re_D=100$, $x_w/D=0.75$].

ence is not found for the $y_w/D=0.75$ case. This point will be elucidated in more detail using point vortex simulations.

The wake behavior for the last three cases, $y_w/D=1.0$, 1.5 , and 2.0 , belong to the third group, where the overall tendency is upward [see Fig. 11(a)]. The trajectory analysis shows that the highest deviation from the reference case occurs for the wire position of $y_w/D=1.0$. The upper vortices follow a higher path than for the other cases. Although the position of the wire is out of the upper shear layer of the cylinder, the effect on the trajectories is prominent. Especially in the trajectories of the upper row vortices, there is a considerable deviation observed from the reference situation.

FIG. 10. Wake properties obtained from SEM simulations at the wire positions of $y_w/D=0.75$ and $y_w/D=0.875$ for $Re=100$. (a) Vortex trajectories, (b) wake centerlines, and (c) vortex strengths [$Re_D=100$, $x_w/D=0.75$].

The vortex centerlines that are shown in Fig. 11(b) confirm the upward deflection of the wakes for the three cases. It can easily be noted that the highest upward deflection is for the $y_w/D=1.0$ case, which has stronger lower vortices than the other cases [see Fig. 11(c)]. The lower vortices in all three cases have almost the same strength but are weaker compared to the reference case.

In Fig. 12, a comparison of the numerical and experimental results is shown. Figure 12 is obtained by superposition of the numerically calculated vortex trajectories and the flow visualization results, as shown in Fig. 1. The top figure shows the comparison for the nonwired case. Both the nu-

FIG. 11. Wake properties obtained from SEM simulations at the wire positions of $y_w/D=1.0$, $y_w/D=1.5$, and $y_w/D=2.0$ for $Re=100$. (a) Vortex trajectories, (b) wake centerlines, and (c) vortex strengths [$Re_D=100$, $x_w/D=0.75$].

merical and experimental results show the same trajectory patterns. For the $y_w/D=0.75$ case, the downward deflection of the upper vortex row in the experimental results is larger than in the numerical result [see Fig. 12(b)]. The lower vortex row trajectory matches the flow visualization results quite well. For $y_w/D=1.0$, the wake axis moves upward in both the experiments and the calculations [Fig. 12(c)]. Also, the individual vortex trajectories show the same trend, although the negative deflection in the lower vortex row is somewhat larger in the experiments.

D. Assessment of vortex strengths

From Figs. 10(c) and 11(c), it can be seen that the presence of a wire has a relatively large impact on the circulation values for both the upper and lower vortex rows. In Table V the circulation values are presented for downstream position $x/D=15$. From this table, it can be seen that for wire position values $y_w/D \geq 0.875$, the upper vortices become weaker due to the presence of the wire and the lower vortices become stronger, and the question could rise why that is so. To answer this question, further assessment of the effect of the wire on the vortex strengths can be done by evaluating the vorticity produced by the main cylinder and the wire. For this purpose, the total period averaged vorticity flux defined in Eq. (8) is used.

In Fig. 13(a), the values of Φ_U and Φ_L are shown with respect to the wire position. It is obvious that despite the asymmetry in the wake, the total circulation entering the wake from both sides of the cylinder is constant, i.e., $\Phi \approx |\Phi_U| \approx \Phi_L$, and this constant depends on the position of the wire. Assuming that all the circulation transported into the wake during one shedding period ends up in a vortex, one would expect the quantity ΦT_{shed} to be directly proportional to the average vortex strength $\Gamma_{av} = (|\Gamma_U| + \Gamma_L)/2$, i.e., $\Phi T_{shed} \propto \Gamma_{av}$ or $\Phi \propto \Gamma_{av} f_{shed}$. From Figs. 13(a) and 13(b), it can be seen that there is indeed a high correlation between the two curves of Φ and $\Gamma_{av} f_{shed}$. As a measure for the vortex strengths, the circulation values from Figs. 9(c), 10(c), and 11(c) at the downstream position of $x/D=15$ are taken, as presented in Table V.

As can be seen from Figs. 7 and 13(a), for each wire position, Φ and f_{shed} are highly correlated for both the upper and lower halves of the wake. Thus, when Γ_U is reduced by the effect of the wire, then Γ_L should increase in order to fulfill the condition $\Phi \propto \Gamma_{av} f_{shed}$. This explains the increase of the lower vortex strengths for the $y_w/D=0.875$ and 1.0 cases. On the other hand, as concluded from Table V for the $y_w/D=1.5$ and 2.0 cases, the upper vortices are weaker as compared to the nonwired case but now the lower ones remain almost at the same strength. This looks in contradiction with the discussion above. However, examining the instantaneous vorticity fields in Fig. 14 for these two cases reveals that the vorticity generated by the wire does not directly contribute to the vortex formation but the negative vorticity originating from the wire seems to interact with the upper vortex that is shed from the main cylinder at some distance after its formation. Probably, this explains why the Strouhal number for these two cases is almost the same as for the nonwired case. It is likely that this interaction causes the upper vortices to become weaker without affecting the strengths of the lower vortices.

E. Vortex arrangement in the wake

The point vortex approach is used to evaluate the effect of the wire on the vortex arrangement in the wake. Each vortex that is out of the formation region is assumed as a point vortex. In Fig. 4, the layout of the wake was shown. The vortex arrangement is assessed using the vortex distance ratio δ_1/δ_2 as previously defined in Sec. II D. For the von

FIG. 12. (Color online) Snapshots from flow visualization experiments (black and white) and vortex trajectories obtained from SEM simulations (black solid lines) [$Re_D=100$, $x_w/D=0.75$].

Kármán vortex street configuration, the ratio of δ_1/δ_2 is equal to 2, as shown in Fig. 15(a). Other possible vortex arrangements are also shown in Figs. 15(b) and 15(c) according to value of the distance ratio.

In Fig. 16, the distance ratio δ_1/δ_2 , as deduced from SEM calculations, is shown for the different cases. The distance ratio is equal to 2 for the single cylinder case where there is no deflection at all. Throughout the domain, the δ_1/δ_2 ratio is slightly above 2 for the $y_w/D=0.5$ and 0.625 cases. For the $y_w/D=0.75$ case, the ratio is substantially larger than 2 but slowly decreasing downstream. For the $y_w/D=0.875$ case, the curve crosses the $\delta_1/\delta_2=2$ line around $x/D=15$. This point corresponds more or less to the point where the wake deflection changes from downward to upward. For the case $y_w/D\geq 1.0$, the distance ratio curves always remain below 2. The most severe trend is for the $y_w/D=1.0$ case where the divergence of the δ_1/δ_2 curve is the highest.

Point vortex simulations are done for the assessment of the vortex arrangement and strength difference on the wake deflection. The quantitative values used in the model are in the same order of magnitude as the values coming out of the

TABLE V. Circulation values of vortices at downstream position $x/D=15$.

Wire position	$ \Gamma_U $	Γ_L
No wire	1.633	1.633
$y_w/D=0.5$	1.671	1.636
$y_w/D=0.625$	1.666	1.598
$y_w/D=0.75$	1.596	1.648
$y_w/D=0.875$	1.267	1.963
$y_w/D=1.0$	1.273	1.980
$y_w/D=1.5$	1.347	1.745
$y_w/D=2.0$	1.340	1.735

FIG. 13. The effect of wire position on (a) the total period averaged vorticity flux at cross section $x/D=1$ ($|\Phi_U|$: upper half of the wake; Φ_L : lower half of the wake) and (b) circulation times shedding frequency at $x/D=15$ (Γ_U : upper vortices; Γ_L : lower vortices).

FIG. 14. Instantaneous vorticity fields of (a) $y_w/D=1.5$ and (b) $y_w/D=2.0$.

numerical simulations discussed above. First, the behavior of vortices with equal strengths and then the arrangement with stronger upper vortices are evaluated.

1. Equal vortex strengths

The first part of the simulations comprises of the evaluation of the vortex distance ratio. For this purpose, the vortex strengths are taken to be $|\Gamma_U|=|\Gamma_L|=2$, where Γ_U and Γ_L are the strengths of upper and lower vortices, respectively. The point vortices are initially distributed according to the spacing ratio of $a/\delta_1=0.281$ for which the von Kármán vortex street is considered to be stable. As shown in Fig. 17(a), the simulation results for the von Kármán vortex street show that there is no deflection in the trajectories. However, when the upper vortices are moved downstream in the initial vortex arrangement, i.e., to the right in Fig. 4, and the simulation is repeated, the trajectory of the vortices show a downward deflection. It should be noted that in this configuration, the spacing ratio is $\delta_1/\delta_2=2.4$ and the vortex arrangement is as in Fig. 15(c). Similarly, when they are moved upstream, the wake goes upward and the spacing ratio is $\delta_1/\delta_2=1.6$, as shown in Fig. 15(b). The point vortex simulation results, which are presented here, show that modified vortex arrangement and wake deflection can be achieved without having strength difference between the vortices. In the modified wake vortex arrangement, the induced vertical velocity components v_j of Eq. (10) are not canceled out anymore. Because of this nonzero vertical velocity component, wake deflection is seen.

2. Stronger upper vortices

In the second part of the point vortex simulations, the initial vortex configuration is fixed in order to evaluate the effect of the strength difference. The configuration has an initial vortex distribution of $a/\delta_1=0.281$ like the von Kármán vortex street configuration. The simulations are done

FIG. 15. Point vortex layouts for different spacing ratios.

for the values $\Gamma_U=-2$ and $\Gamma_L=1.2$. The resulting vortex trajectories are shown in Fig. 17(b) where the tendency of the wake is downward.

This situation is explained as follows. In the point vortex model, the resultant horizontal velocity of the lower vortices, $u_j|_{\text{lower}}$ in Eq. (9), is calculated as the free-stream velocity minus the total induced velocity. If the upper vortices are stronger, then they will induce a higher negative horizontal velocity on the lower vortices. An increased induced negative horizontal velocity of the lower row makes the lower vortices to move slower than the upper vortices. Thus, the lower vortices become closer to the upstream upper vortices as they move downstream. This results in a point vortex arrangement with a spacing ratio of $\delta_1/\delta_2 > 2$ as in Fig. 15(c). In the modified wake vortex arrangement, the induced vertical velocity components v_j are not canceled out anymore. A negative vertical velocity is induced for each vortex in the array that makes the wake to go downward. The opposite conclusion is also true. When the lower vortices are

FIG. 16. Downstream variation horizontal distance ratio δ_1/δ_2 . Note that $\delta_1/\delta_2=2$ corresponds to stable von Kármán vortex street. The results are obtained from SEM simulations [$Re_D=100$, $x_w/D=0.75$].

stronger, the upper ones move slower and become closer to the upstream lower vortices and the wake goes up. A detailed analysis for the similar situation of heated cylinder wake can be found in Refs. 17 and 18. In that case, the upper vortices are stronger than the lower vortices and the wake trajectory moves downward.

F. Lift and drag characteristics of main cylinder

In addition to its wake characteristics, lift and drag characteristics of the main cylinder are also evaluated for different positions of the wire for which the results are illustrated in Fig. 18. The comparison of time averaged drag coefficients in Fig. 18(a) shows that a drag reduction is obtained

FIG. 17. Point vortex simulations for various cases. (a) Effect of position change of upper vortices, $|\Gamma_U|=|\Gamma_L|$. (b) Effect of strength difference, $|\Gamma_U| > |\Gamma_L|$.

for all wire positions. The highest reduction compared to the single cylinder case is 6.4% and seen at wire position of $x_w/D=0.75$. This value is lower than the value reported by Dalton *et al.*¹⁶ for the same Reynolds number but for a different configuration. They found a drag reduction of 33% when the vortex shedding was suppressed. The variation of the Strouhal number as presented in Fig. 7 and the mean drag coefficient show a similar behavior as function of the wire position, however, with a slightly different location for the minimum value. The correlation in the trend is in good agreement with the conclusions of Strykowski and Sreenivasan,⁹ who stated that mean drag reduction can also be seen in some cases where the vortex shedding frequency is reduced or suppressed. The fluctuating lift coefficient in Fig. 18(b) is following the same trend as the mean drag coefficient. Similarly, the highest damping of the fluctuating lift coefficient occurs again at the same location with 46.9% reduction when compared to the single cylinder case.

Breaking the symmetry of the circular cylinder flow with a wire clearly shows its effect on mean drag coefficients and fluctuating lift coefficients as well as on mean lift coefficients. It should be recalled from the previous sections that the highest uniform downward deflection occurs at wire po-

FIG. 18. Comparison of lift and drag characteristics of the main cylinder. (a) Mean drag coefficient $C_{D_{mean}}$. (b) Mean lift coefficient $C_{L_{mean}}$ and fluctuating lift coefficient $C_{L_{rms}}$.

sition of $y_w/D=0.75$, where minimum mean drag and fluctuating lift coefficients are seen. This position also corresponds to the wire location where the highest positive mean lift coefficient is found [Fig. 18(b)]. It is likely that a downward deflection is the signature of a mean positive lift acting on the main cylinder.

It is known from basic fluid dynamics theory²⁷ that a positive lift is related to a negative circulation around the cylinder. This negative circulation, in turn, results in downward deflected streamlines, i.e., a negative deflection of the vortex street. This global picture seems to hold for wire position $y_w/D=0.75$. For other positions of the wire, less clear or even conflicting results are observed.

IV. DISCUSSION AND CONCLUDING REMARKS

The effect of a wire is investigated using numerical simulations using the spectral element methods. The effect is explored by changing the vertical position of the wire that was placed on one side of the cylinder. The Reynolds number based on the diameter of the main cylinder is fixed to $Re=100$. The major findings are summarized in Table VI. The primary effect of the wire is reducing the velocity fluctuations in the vortex formation region of the cylinder. Additionally, the shedding frequency is also reduced. The amount of reduction depends on the position of the wire. The

TABLE VI. Summary of the Strouhal number, the distance ratio, the strength difference $|\Gamma_U| - |\Gamma_L|$, values at $x/D=20$, and wake deflection direction for different wire positions.

Configuration	St number	δ_1/δ_2	$ \Gamma_U - \Gamma_L $	Deflection
No wire	0.1660	$\delta_1/\delta_2=2$	0.000	No deflection
$y_w/D=0.5$	0.1658	$\delta_1/\delta_2 > 2$	0.035	Downward
$y_w/D=0.625$	0.1624	$\delta_1/\delta_2 > 2$	0.064	Downward
$y_w/D=0.75$	0.1532	$\delta_1/\delta_2 > 2$	-0.063	Downward
$y_w/D=0.875$	0.1503	$\delta_1/\delta_2 > 2$	-0.714	Downward
$y_w/D=1.0$	0.1569	$\delta_1/\delta_2 < 2$	-0.644	Upward
$y_w/D=1.5$	0.1656	$\delta_1/\delta_2 < 2$	-0.341	Upward
$y_w/D=2.0$	0.1671	$\delta_1/\delta_2 < 2$	-0.351	Upward

results indicate that there is an optimal point for maximizing the effect of the wire $y_w/D=0.875$, which is slightly over the maximum vorticity line in the shear layer. In agreement with the discussion of Strykowski and Sreenivasan,⁹ it can be concluded that the effect of the wire is to damp the growth of disturbances, which, in turn, results in a lower shedding frequency. However, it was shown in the studies of Sakamoto and Haniu¹⁵ and Parezanovic and Cadot²⁸ that for high Reynolds numbers, the presence of the control cylinder does not always reduce the shedding frequency. In their studies, the frequency reduction depended on the position of the control cylinder and was associated with the bending of the separated shear layer due to the presence of the control cylinder and feeding of the shear layer with vorticity generated by the control cylinder.

The secondary effect of the wire, as primarily studied in this paper, is seen in the wake of the cylinder, i.e., the kinematics of the vortices. The wire results in a modified vortex arrangement in the wake and a strength difference between the upper and lower vortices. For the $y_w/D=0.75$ case, both the upper and lower vortices have almost the same strength as compared to the reference single cylinder case. However, the placement of the wire apparently induces a different formation process for the upper and lower row vortices, causing the upper vortices to position themselves closer to the previously shed lower vortices. As shown in the point vortex simulations, the resulting modification of the vortex arrangement causes the downward deflection of the wake. Similarly, the wake goes upward for the opposite case where the upper vortices are closer to the subsequently shed lower vortices. When the change in vortex arrangement is combined with a strength difference, the effect of the wire becomes even more severe, as in the $y_w/D=1.0$ case. In this situation, the stronger lower vortices induce a higher negative horizontal velocity for the upper vortex row. This higher induced velocity makes each upper vortex move slower and become closer to the subsequently shed lower vortex. Another interesting result is seen in the $y_w/D=0.875$ case, where the upper vortices are positioned closer to the previously shed lower vortices in the formation region, like in the $y_w/D=0.75$ case. Because of this, the wake has a downward tendency like in the $y_w/D=0.75$ case. On the other hand, the higher strength of the lower vortices makes the upper vortices move slower

and become closer to the subsequently shed lower vortices. Because of this reason, the wake in this particular case changes its tendency in the downstream region of the wake and starts to go upward. This phenomenon can also be seen in the visualization results for the $y_w/D=1.0$ case as presented in Fig. 1.

Based on the above observations, a hypothesis about the wake deflection is formulated: *the deflection of the wake is primarily caused by a modification of the vortex arrangement in the wake.* The strength difference between the upper and lower row vortices is only a tool for achieving a modification of the vortex street like in the case of a heated cylinder.^{17,18} A repositioning of the vortices is a necessary and sufficient condition for the wake deflection to occur. The conclusions from the present study state the following.

- (1) $\delta_1/\delta_2=2$: undisturbed von Kármán vortex street with no deflection.
- (2) $\delta_1/\delta_2>2$: downward deflection.
- (3) $\delta_1/\delta_2<2$: upward deflection.

As concluding remarks, it can be said that placing a very thin wire in the near wake of a cylinder not only changes the vortex shedding frequency by effecting the velocity fluctuations but also changes the formation process of the vortices. The change in the formation process results in a modified vortex arrangement that causes the deflection of the wake.

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