

NUMERICAL INVESTIGATION OF FLOW PAST A ROTATING CYLINDER IN A CONFINED TWO-DIMENSIONAL CHANNEL

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Abstract. In the paper, two-dimensional incompressible flow past a circular cylinder located in a plane channel is considered. The effect of cylinder rotation on force coefficients, pressure distribution on the cylinder surface and wake structure is analysed numerically. Rotating and non-rotating cases are compared under the same geometrical and computational conditions. The finite element method (FEM) is used for numerical calculations. Mean and fluctuating force coefficients, surface-pressure distribution, wake profiles, and selected probe signals are presented and discussed. Particular attention is paid to the asymmetry of the near-wake region and to spectral properties of the obtained solution.

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1. Introduction

Computational methods are commonly used in engineering analysis [1, 2]. In the present paper, they are applied to laminar flow past a single circular cylinder located in a plane channel. The confinement is kept constant, and cylinder rotation is the only varying parameter. This change affects the force balance, the wake asymmetry, and the spectral response of the flow. For $Re = 100$, the non-rotating confined case can be treated as a reference case for drag, lift, and shedding in a bounded domain [3]. It is also known that, in unconfined low- Re flow, cylinder rotation changes these quantities and may suppress periodic shedding when the rotation ratio is sufficiently high [4]. Direct comparisons for the combined effect of confinement and rotation are less frequent. Prasad et al. considered the two-dimensional laminar problem for broader ranges of parameters [5].

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In recent years, this problem has been discussed in a wider context. Nguyen et al. reviewed flows past confined cylinders [6], while Lu et al. analysed spectral properties of confined wakes [7]. Studies devoted to higher Reynolds numbers and flow control extend the available background [8, 9]; however, they do not resolve the case considered here.

The presented paper compares the flow past a fixed cylinder ($\alpha = 0$) and a rotating cylinder ($\alpha = 1$) for $Re = 100$ and $B \approx 1/6$. The analysis includes mean and fluctuating force coefficients, their pressure and viscous components, mean pressure distribution on the cylinder surface, selected wake profiles, and probe signals. The Strouhal number is determined when a distinct spectral peak is obtained.

2. Mathematical model

Considered flow is two-dimensional, incompressible, and laminar. The channel region is denoted by $\Omega \subset \mathbb{R}^2$. Its boundary is divided into the inlet Γ_{in} , the outlet Γ_{out} , the channel walls Γ_w , and the cylinder wall Γ_{cyl} , so that $\partial\Omega = \Gamma_{\text{in}} \cup \Gamma_{\text{out}} \cup \Gamma_w \cup \Gamma_{\text{cyl}}$. The flow is governed by the following equations:

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

$$\rho \left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} \right) = -\nabla p + \mu \nabla^2 \mathbf{u} \quad \text{in } \Omega \times (0, t_{\text{end}}]. \quad (2)$$

where $\mathbf{u} = (u, v)$ is the velocity field, p is the pressure, ρ is the density, and μ is the dynamic viscosity.

The above equations are completed by the following boundary conditions:

$$\mathbf{u} = (U_{\text{ref}}, 0) \quad \text{on } \Gamma_{\text{in}}, \quad (3)$$

$$\mathbf{u} = \mathbf{0} \quad \text{on } \Gamma_w, \quad (4)$$

$$\mathbf{u} = \mathbf{u}_{\text{cyl}} \quad \text{on } \Gamma_{\text{cyl}}, \quad (5)$$

$$p = 0 \quad \text{on } \Gamma_{\text{out}}. \quad (6)$$

At the outlet, only the pressure level is prescribed, while velocity is not imposed there. In the case of the rotating cylinder the wall velocity is described by the relation:

$$\mathbf{u}_{\text{cyl}}(x, y) = \omega \left(-(y - y_c), x - x_c \right), \quad (7)$$

where (x_c, y_c) is the cylinder centre and ω is the angular velocity. The reference case has $\omega = 0$.

The dimensionless parameters used in the analysis are defined as follows:

$$Re = \frac{\rho U_{\text{ref}} D}{\mu}, \quad \alpha = \frac{\omega D}{2U_{\text{ref}}}, \quad B = \frac{D}{H}, \quad (8)$$

where D is the cylinder diameter and H means the channel height.

The reference dynamic pressure is given by:

$$q_{\text{ref}} = \frac{1}{2} \rho U_{\text{ref}}^2. \quad (9)$$

Using this quantity, the pressure coefficient on the cylinder surface can be written in the form:

$$C_p = \frac{p}{q_{\text{ref}}}. \quad (10)$$

The force and moment coefficients are defined by:

$$C_D = \frac{F_x}{q_{\text{ref}} D}, \quad C_L = \frac{F_y}{q_{\text{ref}} D}, \quad C_M = \frac{M_z}{q_{\text{ref}} D^2}, \quad (11)$$

where positive F_y is directed upward, while positive M_z and ω are counter-clockwise in the (x, y) plane. The angle θ used in the pressure distribution is measured counter-clockwise from the positive x direction. For $\alpha = 1$, the upper point of the cylinder moves against the inlet flow.

3. Numerical method

Standard P_1 finite elements are used on conforming triangular meshes for both velocity components and pressure. Assuming that $\{N_i\}_{i=1}^N$ are nodal basis functions, the discrete velocity and pressure fields can be written in the form:

$$\mathbf{u}_h(\mathbf{x}, t) = \sum_{j=1}^N N_j(\mathbf{x}) \mathbf{U}_j(t), \quad p_h(\mathbf{x}, t) = \sum_{j=1}^N N_j(\mathbf{x}) P_j(t). \quad (12)$$

The equal-order approximation is used in a segregated pressure-correction algorithm, not in a monolithic mixed formulation. The SUPG term is introduced only in the provisional momentum equation and no PSPG pressure stabilization is used. Time discretization is carried out using a segregated implicit scheme. For the velocity field known at time t^n , the provisional momentum equation for each Cartesian component has the form:

$$\left[\frac{1}{\Delta t} \mathbf{M} + \mathbf{C}(\mathbf{u}^n) + \mathbf{K}_v + \mathbf{S}_{\text{SUPG}} \right] \tilde{\mathbf{U}}^{n+1} = \frac{1}{\Delta t} \mathbf{M} \mathbf{U}^n + \mathbf{b}_u^{n+1}, \quad (13)$$

where $\mathbf{M}$ is the consistent mass matrix, $\mathbf{C}(\mathbf{u}^n)$ denotes the convection matrix assembled for the currently known velocity field, $\mathbf{K}_v$ is the diffusion matrix connected with the laminar kinematic viscosity $\nu = \mu/\rho$, and $\mathbf{b}_u^{n+1}$ contains the Dirichlet boundary contributions.

The pressure field was then obtained from the discrete continuity correction:

$$\mathbf{L}_\rho \mathbf{P}^{n+1} = -\frac{1}{\Delta t} \mathbf{D} \tilde{\mathbf{U}}^{n+1}, \quad (\mathbf{L}_\rho)_{ij} = \int_{\Omega} \rho^{-1} \nabla N_i \cdot \nabla N_j d\Omega, \quad (14)$$

with the pressure level fixed by Eq. (6). On the inlet, channel walls, and cylinder wall, no pressure value is prescribed. Natural homogeneous Neumann conditions are used there. The nodal velocities were corrected according to:

$$\mathbf{U}^{n+1} = \tilde{\mathbf{U}}^{n+1} - \Delta t \mathbf{M}_\rho^{-1} \mathbf{G} \mathbf{P}^{n+1}, \quad (15)$$

where $\mathbf{G}$ is the discrete pressure-gradient operator and $\mathbf{M}_\rho$ is the nodal mass-density scaling used in the correction stage.

The SUPG contribution in Eq. (13) was assembled elementwise as:

$$\begin{aligned} \mathbf{S}_{\text{SUPG}}^{(e)} &\sim \int_{\Omega_e} \tau_e (\mathbf{u} \cdot \nabla N_i) (\mathbf{u} \cdot \nabla N_j) d\Omega, \\ \tau_e &= \left[\left(\frac{2\|\mathbf{u}\|}{h_{\parallel}} \right)^2 + \left(\frac{C_k \nu}{h_{\parallel}^2} \right)^2 + \left(\frac{C_t}{\Delta t} \right)^2 \right]^{-1/2}. \end{aligned} \quad (16)$$

where $h_{\parallel}$ is the directional element size along the local flow. The constants were set to $C_t = 1.0$ and $C_k = 2.0$.

The systems resulting from Eqs. (13)-(15) are assembled and solved in an in-house finite element code. Two momentum equations are solved separately after direct imposition of the Dirichlet boundary conditions on the inlet, the channel walls and the cylinder wall. The pressure equation is assembled from the divergence of the provisional velocity field with outlet pressure equal to zero. All linear algebraic systems are solved using the PARDISO solver, after which the essential velocity constraints are imposed again. Pressure field, inlet-outlet flux balance, and discrete divergence were monitored. No alternating pressure modes or mass-balance drift were observed.

4. Geometry and setup

The height of the channel is equal to $H = 0.60 \text{ m} = 6D$, while its length is $L_x = 2.65 \text{ m}$. The cylinder diameter is $D = 0.10 \text{ m}$. The cylinder centre is located at the point $(x_c, y_c) = (0.60, 0.30) \text{ m}$, which gives the blockage ratio $B \approx 0.1667$. In calculations, the following reference quantities are assumed: $\rho = 1.205 \text{ kg m}^{-3}$, $\mu = 1.81 \cdot 10^{-5} \text{ Pa s}$ and $U_{\text{ref}} = 0.01502 \text{ m s}^{-1}$. For these data the Reynolds number is equal to about $Re = 100$. Two cases are compared, namely $\alpha = 0$ and $\alpha = 1$.

The diagnostic arrangement shown in Figure 1 is used to connect the surface loading with the wake structure and with spectral properties of the flow. Mean profiles are taken at $x = 0.75, 0.85$ and 1.05 m , namely, at $x = x_{\text{te}} + 1D$, $x = x_{\text{te}} + 2D$ and $x = x_{\text{te}} + 4D$. In this way, three successive cross-sections are obtained in order to observe the downstream decay of wake asymmetry. Two wake probes are located at $x = x_{\text{te}} + 1D$ and $y = y_c \pm 0.25D$, so that the upper and lower wake behaviour directly behind the cylinder can be examined. These local signals are used later in statistical and spectral analysis.

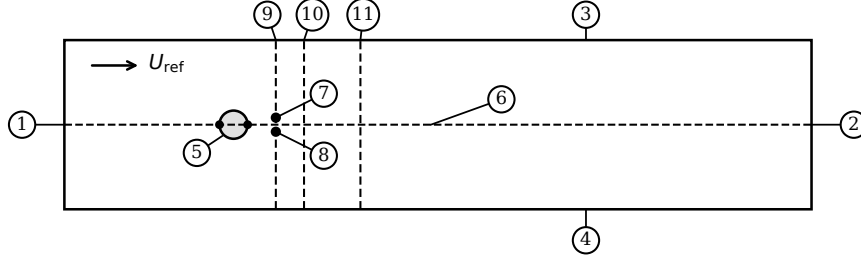


Fig. 1. Computational domain used in the calculations. The numbered markers denote: 1 – inlet, 2 – outlet, 3 – upper stationary wall, 4 – lower stationary wall, 5 – cylinder wall, 6 – centerline, 7 – upper wake probe, 8 – lower wake probe, 9 – sec_1D, 10 – sec_2D, and 11 – sec_4D

Sensitivity analysis is performed for three meshes containing 25,947 nodes, 101,480 nodes, and 402,326 nodes. The time step study is carried out for the mesh with 101,480 nodes and for $\Delta t = 0.02$ s, 0.01 s and 0.005 s. The main long-time calculations for $\alpha = 1$ and $\alpha = 0$ are performed using the 101,480-node mesh, the time step $\Delta t = 0.01$ s, and the final time $t_{\text{end}} = 200$ s.

Online statistical averaging starts at $t = 60$ s in order to exclude the initial transient part of the solution. Tables, profiles, and spectra are reported for the time interval 80 s - 200 s, which means that an additional buffer of 20 s is kept after the beginning of statistics. Forces are sampled at every time step. Postprocessing includes cylinder forces, pressure on the cylinder surface, wake-probe signals, and profiles along the centerline and on sec_1D, sec_2D, and sec_4D.

5. Verification and numerical reliability checks

Sensitivity of the solution to the time step is checked on the mesh containing 101,480 nodes in the time interval 10 s - 30 s. This interval is used only for parameter selection; final statistics and spectra are obtained later from 80 s - 200 s. Reduction of the time step from $\Delta t = 0.02$ s to 0.01 s and 0.005 s changes the mean drag coefficient $\overline{C_D}$ from 1.0718 to 1.0465 and 1.0340, respectively. At the same time, the value of $C_{L,\text{rms}}$ changes from 0.3274 to 0.3418 and 0.3499. The relative L_2 difference of the mean pressure coefficient on the cylinder surface, calculated with respect to the result obtained for $\Delta t = 0.005$ s, decreases from 0.0404 to 0.0146 and then to 0.0. For this reason, the time step $\Delta t = 0.01$ s is assumed in further long-time calculations.

Mesh sensitivity is analysed for $\Delta t = 0.01$ s in the same time interval 10 s - 30 s. Three meshes containing 25,947 nodes, 101,480 nodes, and 402,326 nodes are taken into account. The obtained mean drag coefficients are equal to $\overline{C_D} = 1.0710$, 1.0465, and 1.0345, respectively, while the values of $C_{L,\text{rms}}$ are 0.3453, 0.3418, and 0.3411. The corresponding relative differences $L_2(C_p)$ with respect to the finest-mesh result are equal to 0.0148, 0.0065, and 0.0. On this basis, the mesh with 101,480 nodes is selected for calculations performed for $\alpha = 1$ and $\alpha = 0$.

The final reporting interval 80 s - 200 s contains 12,001 samples and gives the frequency resolution equal to 0.00833 Hz. For the case $\alpha = 0$, the lift coefficient signal and the transverse velocity signal at the upper wake probe remain at residual levels in this interval. The corresponding values are $C_{L,rms} = 3.60 \cdot 10^{-4}$ and $v_{y,rms} = 2.63 \cdot 10^{-5}$. Therefore no isolated spectral peak is identified and no Strouhal number is assigned. For the case $\alpha = 1$, both signals give the same dominant frequency equal to about $f = 0.0333$ Hz, which corresponds to $St \approx 0.222$.

6. Results and discussion

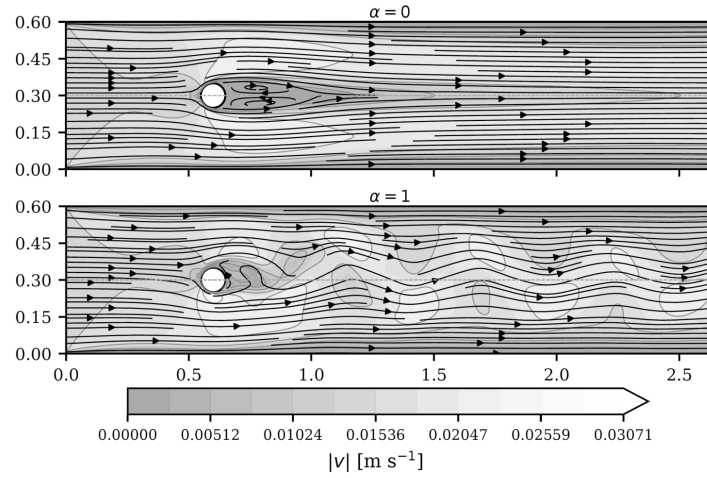


Fig. 2. Instantaneous speed contours and streamlines at $t = 200$ s for $\alpha = 0$ and $\alpha = 1$ on the 101,480-node mesh

Figure 2 presents the instantaneous structure of the near wake obtained at the end of the main calculations. For the case $\alpha = 0$, the wake remains approximately symmetric with respect to the channel centreline, and the streamlines recover in a relatively smooth way behind the cylinder. For the rotating case $\alpha = 1$, the recirculation zone and the shear layers are visibly shifted, and the wake shows a clear lateral asymmetry.

6.1. Force signatures

Cylinder rotation changes the mean force state and also increases the level of fluctuations. Calculations performed in the time interval 80 s - 200 s on the mesh containing 101,480 nodes for $\Delta t = 0.01$ s show that the non-rotating case remains close to a steady state. For $\alpha = 0$, one obtains $\overline{C_D} = 0.9154$, $\overline{C_L} = 2.90 \cdot 10^{-4}$, and $C_{L,rms} = 3.60 \cdot 10^{-4}$. For the rotating cylinder, i.e. for $\alpha = 1$, the mean drag coefficient decreases to $\overline{C_D} = 0.8279$, which is about 9.6 % lower than for $\alpha = 0$, while the mean

lift coefficient changes to $\overline{C_L} = -2.5386$. At the same time, the fluctuation levels become distinctly higher. For $\alpha = 1$, the obtained values are $C_{L,\text{rms}} = 0.3045$ and $C_{D,\text{rms}} = 0.0978$, whereas for $\alpha = 0$ they are equal to $3.60 \cdot 10^{-4}$ and 0.0013 , respectively. The mean moment coefficient also changes both its sign and magnitude, from $-1.31 \cdot 10^{-4}$ to 0.2 .

Table 1. Comparison of the long calculations for $\alpha = 0$ and $\alpha = 1$ on the 101,480-node mesh with $\Delta t = 0.01$ s, evaluated over 80 s - 200 s

Case	$\overline{C_D}$	$\overline{C_L}$	$C_{L,\text{rms}}$	Spectral metric	Main effect
$\alpha = 0$	0.9154	0.0003	0.0004	—	near-steady force response; no resolved spectral peak
$\alpha = 1$	0.8279	-2.5386	0.3045	$St \approx 0.222$	negative mean lift, lower mean drag, coherent oscillation

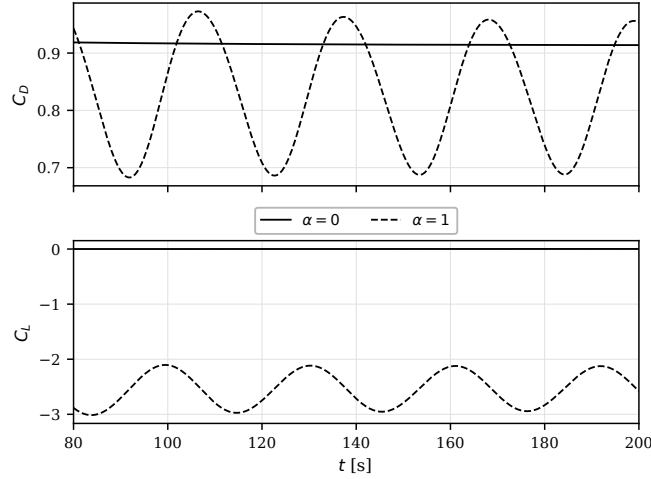


Fig. 3. Time histories of drag and lift coefficients for $\alpha = 0$ and $\alpha = 1$ over 80 s - 200 s

These differences can be directly observed in the force histories presented in Figure 3. For $\alpha = 0$, both coefficients C_D and C_L remain almost constant in the considered time interval, which confirms a nearly steady force response. For $\alpha = 1$, the drag coefficient oscillates around a lower mean value, while the lift coefficient remains clearly shifted below zero, and at the same time exhibits low-frequency oscillations without visible long-time drift. Table 1 summarizes this comparison in a compact form. However, the histories show more clearly that the rotating case differs from the non-rotating one not only with respect to the mean values, but also with respect to the unsteady character of the solution. Repeated oscillation cycles indicate the existence of a dominant time scale.

6.2. Surface pressure distribution

The shift of the lift coefficient observed in Figure 3 results mainly from the pressure component. In the interval 80 s - 200 s, for the case $\alpha = 0$, the integrated pressure contribution is equal only to $\overline{C_{L,p}} = 5.3 \cdot 10^{-5}$, while the viscous contribution is $\overline{C_{L,v}} = 2.37 \cdot 10^{-4}$. For the rotating case $\alpha = 1$, the pressure contribution changes to $\overline{C_{L,p}} = -2.6712$, whereas the viscous contribution changes only to $\overline{C_{L,v}} = 0.1326$. Changes of the drag components are of the same sign but are much smaller. The value of $\overline{C_{D,p}}$ decreases from 1.3136 to 1.2578, while $\overline{C_{D,v}}$ changes from -0.3982 to -0.4299 .

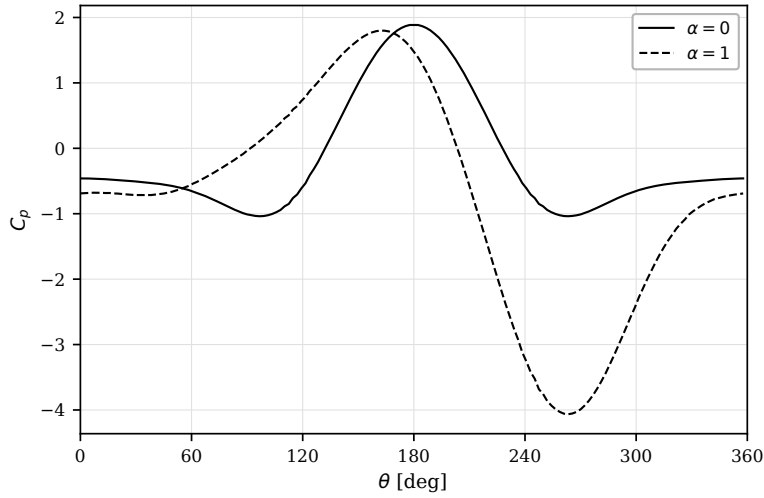


Fig. 4. Mean cylinder-surface pressure coefficient distribution $C_p(\theta)$ for $\alpha = 0$ and $\alpha = 1$, evaluated from boundary samples over 80 s - 200 s

This pressure redistribution is local in character, which is shown in Figure 4. In the angular range $\theta \approx 240^\circ$ - 285° on the lower part of the cylinder, the curve obtained for $\alpha = 1$ is distinctly lower than that for $\alpha = 0$. In turn, in the range $\theta \approx 90^\circ$ - 180° on the upper part of the cylinder, the relation is opposite and the rotating case gives higher values than the reference case. Such a distribution, with higher pressure on the upper side and lower pressure on the lower side, produces a negative resultant transverse force, which is consistent with the sign of $\overline{C_L}$ shown in Figure 3. The relative differences equal to $L_2 = 1.589$ and $L_\infty = 1.605$ indicate that the change is not limited to a narrow angular region.

6.3. Wake structure

The mean wake reflects the same asymmetry that is observed on the cylinder surface (Fig. 5). On sec_1D, the profile of $\overline{v_y}$ for $\alpha = 0$ remains close to zero over the whole section and only a weak antisymmetric variation can be seen. For $\alpha = 1$, the same profile develops a distinct positive lobe followed by a negative lobe of comparable magnitude. This imbalance becomes smaller on sec_2D and smaller

again on sec_4D, where both cases are still different but much closer to each other. This indicates that the strongest transverse asymmetry is limited mainly to the immediate near-wake region.

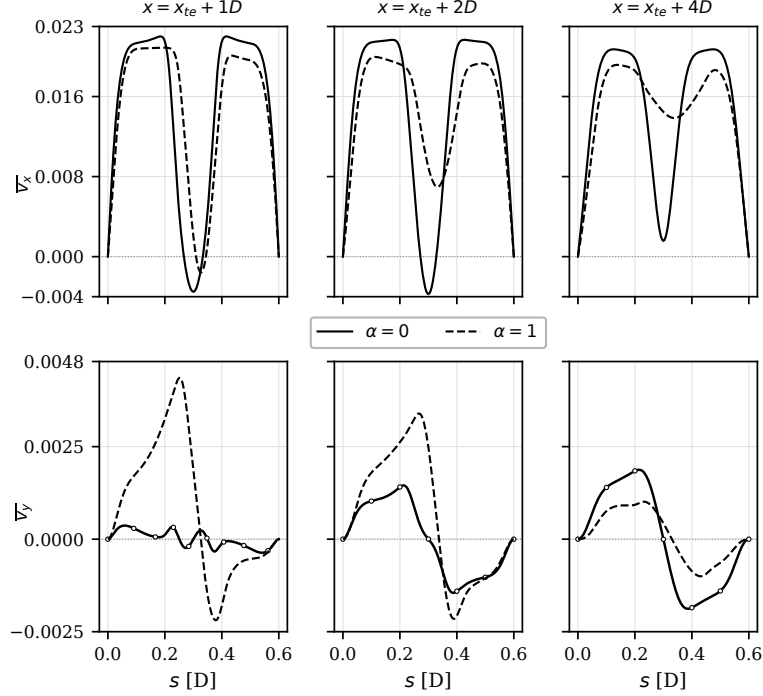


Fig. 5. Mean wake profiles of $\bar{v}_x$ and $\bar{v}_y$ on sec_1D, sec_2D, and sec_4D for $\alpha = 0$ and $\alpha = 1$, evaluated over 80 s - 200 s

The streamwise velocity field is also modified. For $\alpha = 0$, the mean profiles of $\bar{v}_x$ on sec_1D and sec_2D contain a narrow central deficit with local reverse flow. For $\alpha = 1$, this deficit is weaker on sec_1D and disappears on sec_2D, where the profile remains positive over the whole section. On sec_4D, both cases give positive streamwise velocity in the entire cross-section; however, the profile shapes are still different. The curve obtained for $\alpha = 1$ is flatter in the central part of the wake, while the curve for $\alpha = 0$ still shows a deeper central depression. Therefore, the effect of rotation is still visible downstream of the cylinder in both $\bar{v}_y$ and $\bar{v}_x$, and it is not fully described only by the integral force coefficients.

The same near-wake asymmetry is confirmed by two probes located at $x = x_{te} + 1D$ (Fig. 6). For $\alpha = 0$, the upper and lower probes remain almost symmetric. The mean streamwise velocities are equal to $-1.51 \cdot 10^{-3}$ and $-1.50 \cdot 10^{-3}$, while the mean transverse components are equal to $+2.36 \cdot 10^{-4}$ and $-2.39 \cdot 10^{-4}$. For $\alpha = 1$, the upper probe remains close to zero mean transverse velocity, with $\bar{v}_x = -1.56 \cdot 10^{-3}$ and $\bar{v}_y = 3.35 \cdot 10^{-5}$. At the same time, the lower probe shifts to $\bar{v}_x = 9.94 \cdot 10^{-3}$ and $\bar{v}_y = 3.61 \cdot 10^{-3}$.

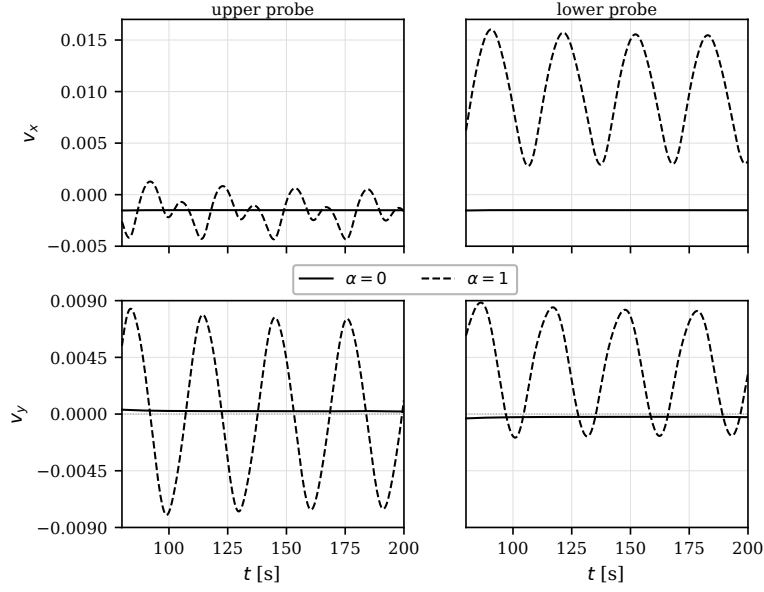


Fig. 6. Instantaneous histories of v_x and v_y at the upper and lower wake probes located at $x = x_{te} + 1D$ for $\alpha = 0$ and $\alpha = 1$ over 80 s - 200 s

The profile metrics lead to the same conclusion in a more compact way. For $\overline{v_y}$, the relative difference between the cases $\alpha = 0$ and $\alpha = 1$ decreases from $L_2 = 8.87$ on sec_1D to 1.17 on sec_2D and 0.538 on sec_4D. The corresponding values of L_∞ are equal to 12.05, 2.10, and 0.685. For $\overline{v_x}$, the relative difference L_2 remains between 0.262 and 0.310 on all three sections. This means that the streamwise velocity field is also changed, although the transverse asymmetry decays faster downstream.

6.4. Spectral response and Strouhal number

The spectra presented in Figure 7 show the dominant time scale of the analysed flow. For the case $\alpha = 0$, neither the lift coefficient signal C_L nor the transverse velocity signal v_y recorded at the upper probe contains an isolated spectral peak in the interval 80 s - 200 s. This near-steady response is related mainly to the present confinement and inlet-wall arrangement, different from benchmark configurations, so no Strouhal number is determined for this case. For $\alpha = 1$, the largest peak appears at the same frequency both in the global and local signal, namely at about $f = 0.0333$ Hz. This corresponds to the period of about 30.0 s and to the value $St \approx 0.222$. This indicates that the force response and the near-wake probe signal are governed by the same dominant low-frequency scale.

For the rotating case $\alpha = 1$, the response is dominated by this frequency; however, the spectrum cannot be treated as strictly single-mode. In the spectrum of C_L , the spectral power decreases rapidly outside the main peak and only weak higher-frequency components remain. In the spectrum of v_y at the upper probe, secondary components are more visible, especially above about 0.07 Hz and in the range

0.09 Hz - 0.10 Hz, although their values are still much smaller than the dominant peak. Thus the local signal contains more than one active scale, but only one isolated peak is sufficiently clear to determine the reported Strouhal number.

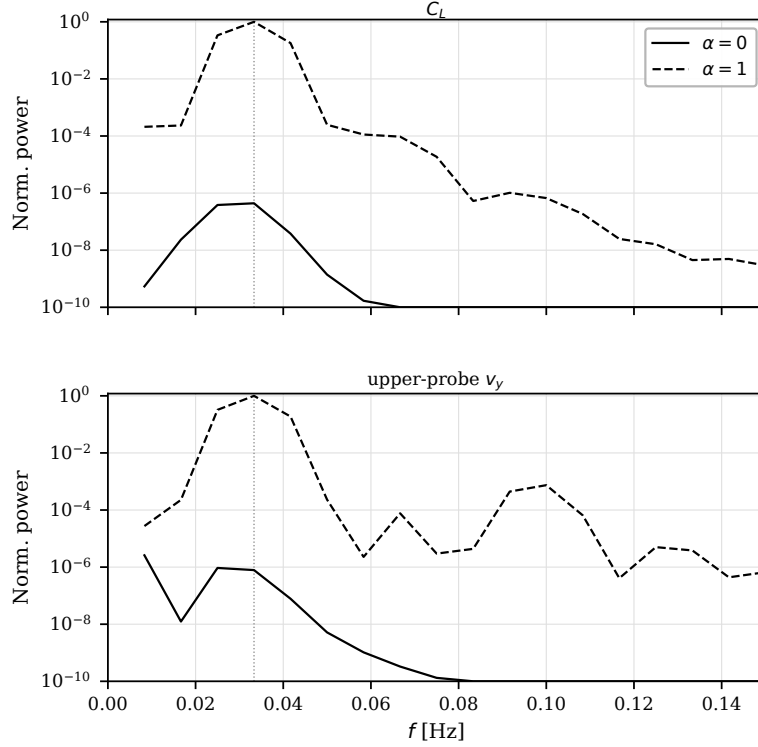


Fig. 7. Panel-wise normalized FFT spectral power of C_L in the upper panel and upper wake-probe v_y in the lower panel for $\alpha = 0$ and $\alpha = 1$ over 80 s - 200 s (each panel is normalized by its own maximum over the two cases and shown on a log scale)

The choice of the time window also affects the obtained result. When the beginning of the analysed interval is shifted between 40 s and 120 s, the calculated Strouhal number changes from 0.200 to 0.250. Therefore, the value $St \approx 0.222$ is related to the interval 80 s - 200 s, which is used consistently in the present comparison.

7. Conclusions

The cylinder rotation reduces the mean drag coefficient from 0.9154 to 0.8279 and changes the mean lift coefficient from $2.90 \cdot 10^{-4}$ to -2.5386 . In the analysed interval, the case $\alpha = 0$ remains close to steady, whereas the case $\alpha = 1$ is unsteady. The change of the mean force state is caused mainly by pressure, since for $\alpha = 1$ one obtains $\overline{C_{L,p}} = -2.6712$ and $\overline{C_{L,v}} = 0.1326$. The wake analysis indicates the strongest transverse asymmetry on sec_1D, its downstream decay, and modification of the streamwise deficit. The reverse-flow core present for $\alpha = 0$ on sec_2D does not

occur for $\alpha = 1$. For $\alpha = 0$, no Strouhal number is determined, while for $\alpha = 1$ both analysed signals give $St \approx 0.222$. Thus, in the considered confined laminar flow, the change from $\alpha = 0$ to $\alpha = 1$ modifies the pressure distribution, the mean wake structure and the time-dependent response of the flow. The conclusion is limited to $Re = 100$, $B \approx 1/6$, and two rotation ratios; trends and transition thresholds require additional values of α .

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