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Abstract.
We perform a series of URANS simulations of the flow over a rotary oscillating cylinder at $Re = 1.4 \times 10^5$ to study the possible reduction of the drag and lift forces acting on the body when the rigid wall is rotary oscillating around the axis of symmetry. Two parameters of the external forcing are varied, i.e. the amplitude of rotation and the frequency. We find that the high-frequency and relatively high-amplitude forcing leads to the drag reduction of 78% compared to the non-rotating case. The oscillations (rms) of drag and lift coefficients are also significantly reduced.

1. Introduction

Most of the flow regimes over bluff bodies feature the unsteady quasi-periodic vortex shedding known as the Karman vortex street. These oscillations affect the drag and lift forces acting on the body. The control of the amplitude and the possible reduction of these forces, in general, is of utmost importance in a wide range of practical applications. In this work we investigate the effect of rotary oscillations of a cylinder of diameter D in a uniform fluid flow with velocity U_∞. The relatively high Reynolds number of interest $Re = U_\infty D/\nu = 1.4 \times 10^5$, where ν is the kinematic viscosity, corresponds to a sub-critical regime with the laminar boundary layer separation but is close to the drag crisis phenomenon ($Re \approx 2.0 \times 10^5$) where the drag coefficient reduces naturally.

Tokumaru and Dimotakis [1] studied the same flow at moderate $Re = 1.5 \times 10^4$ and showed that the drag coefficient can be reduced by 80% if high-frequency rotary oscillating motion of the form

$$U_\theta\Big|_{wall} = \frac{\Omega D}{2}\sin(2\pi f t)$$

is applied to the cylinder wall, where U_θ is the tangential velocity, Ω the oscillation amplitude, f the frequency and t the time. The physical reason behind the significant drag reduction is the transformation of the wake velocity profile which reorganizes and becomes more narrow (see Fig. 1). Shiels and Leonard [2] qualitatively confirmed the results of Tokumaru and Dimotakis with the two-dimensional simulations in the range of $150 \leq Re \leq 1.5 \times 10^4$ stressing that the effect of the drag reduction enhances with the Reynolds number increase. Relatively coarse three-dimensional large-eddy simulations (LES) performed by Du and Dalton [3] at $Re = 1.5 \times 10^4$

also confirmed the results of Tokumaru and Dimotakis although with the drag reduction of 57% instead of optimistic 80% obtained in experiments due to inaccurate method for drag coefficient calculation.

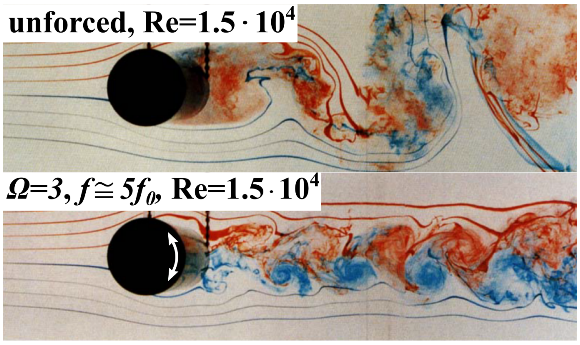

Figure 1. Visualization of the flow with and without the rotary oscillations from experiments [1]. The frequency f_0 corresponds to the natural (unforced) vortex shedding process.

In the present work we use a verified Unsteady Reynolds-averaged Navier-Stokes method with second moment closure Reynolds Stress Model of Jakirlić and Hanjalić [4] (URANS RSM JH) to investigate the effect of rotary oscillations on the drag and lift forces in a broad range of parameters. This model has been previously verified on LES of the same non-rotating case [5] and experimental data [6]. The relatively high Reynolds number $Re = 1.4 \times 10^5$ is of practical importance in contrast with most previous low Re studies. Our precursor work [7] in the low-frequency range ($f = f_0$, where f_0 corresponds to the natural/unforced vortex shedding process) did not reveal drag reduction in agreement with the work of previous investigators. Here we focus on higher-frequency oscillations with $f = 2.5f_0$ which are found optimal by Du and Dalton for $Re = 1.5 \times 10^4$.

2. Computational details

The simulations were performed using the TU Delft in-house unstructured finite-volume computational code T-FlowS, with the cell-centred collocated grid structure. The convective term in the transport equations was discretized by a second-order upwind-biased TVD differencing scheme. The diffusion term was discretized by the second-order central differences. The time-marching was performed using a fully-implicit three-level time scheme. The pressure-velocity coupling was handled by the SIMPLE algorithm. The mesh comprised 2.3×10^6 hexahedral cells. The computational domain was a box with $25D$ length in streamwise and $20D$ in crosswise directions while the spanwise length was $2D$ (see Fig. 2). The center of the cylinder was placed at $10D$ from the inflow boundary with uniform velocity U_∞ and zero free-stream turbulence. The slip conditions were set at the top and bottom boundaries, the convective outflow condition at the outlet and the no-slip condition on cylinder wall. Periodic conditions were imposed in the cylinder axis direction.

3. Results

The central parameter of the problem is the drag and lift coefficients:

$$C_D = 2F_x/(\rho U_\infty^2 S), \qquad C_L = 2F_y/(\rho U_\infty^2 S),$$

where ρ is the density of the fluid and S is the area of the cylinder wall. The force components F_x and F_y acting on the body include the pressure and viscous contributions. We compare the time-averaged value $\overline{C}_D = 1.27$[1] previously obtained for the non-rotating case using URANS

[1] LES [6] provided $\overline{C}_D = 1.24$, the same as the experimental data of Cantwell and Coles [5]

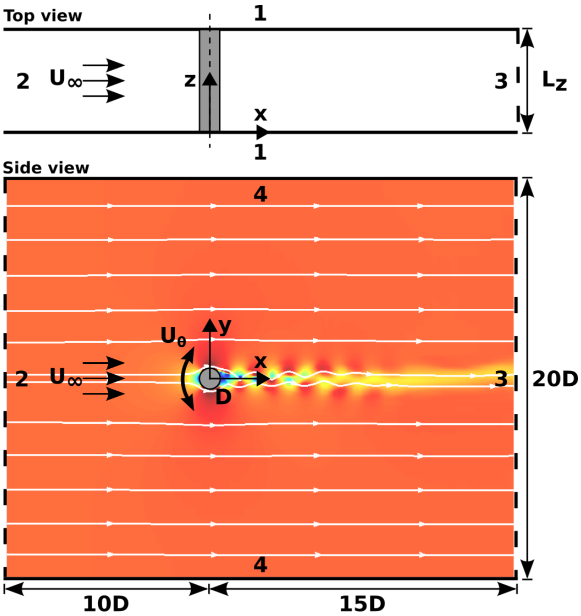

Figure 2. Computational domain. The numbers from 1 to 4 correspond to periodic, inflow, convective outflow and slip conditions.

RSM JH to low-frequency and high-frequency rotary forced regimes. The first one was forced at $f = f_0$ with $f_0 \approx 0.22$, investigated previously [7], did not show significant improvements of the drag characteristics. On the other hand, the second regime with $f = 2.5f_0$ showed substantial decrease of $\overline{C}_D$. All cases were forced with the non-dimensional amplitude $\Omega = 1$, 2 and 3 (value of $\Omega D/U_\infty$). Table 1 shows the value of $\overline{C}_D$ for various Ω and f values. The optimal among considered control parameters are $\Omega = 2$ and $f = 2.5f_0$ where the drag coefficient value ($\overline{C}_D = 0.28$) is reduced by 78% compared to the non-rotating case ($\overline{C}_D = 1.27$).

Table 1. Time-averaged drag coefficient $\overline{C}_D$ at $Re = 1.4 \times 10^5$ for various Ω and f.

	$\Omega = 1$	$\Omega = 2$	$\Omega = 3$
$f = 1.0f_0$	1.30	1.21	1.33
$f = 2.5f_0$	0.56	0.28	0.42

A sample of the time-history of the drag and lift coefficients for various Ω and $f = 2.5f_0$ is presented in Fig. 3. Note that at relatively low $\Omega = 1$ the signal of C_L resembles the one for unforced case with only modulations imposed by rotation. However, for higher Ω the signal is clearly $2.5f_0$-periodic. In practice not only the time-averaged value of C_D is important but also the amplitude of oscillations of the forces. Note that the optimal regime also exhibits the lowest rms values of C_D and C_L. Figure 4 shows the streamlines and axial velocity field (left) and vorticity field (right) for various forcing parameters. As previously mentioned the high-frequency forcing reorganizes the vortical structure of the wake reducing the velocity defect leading to the smaller drag coefficient. Future work will be devoted to extending the parameter $\Omega - f$ map.

4. Conclusion

We performed a series of URANS simulations of the flow over a rotary oscillating cylinder at $Re = 1.4 \times 10^5$. Low- and high-frequency oscillations were studied with various amplitudes of

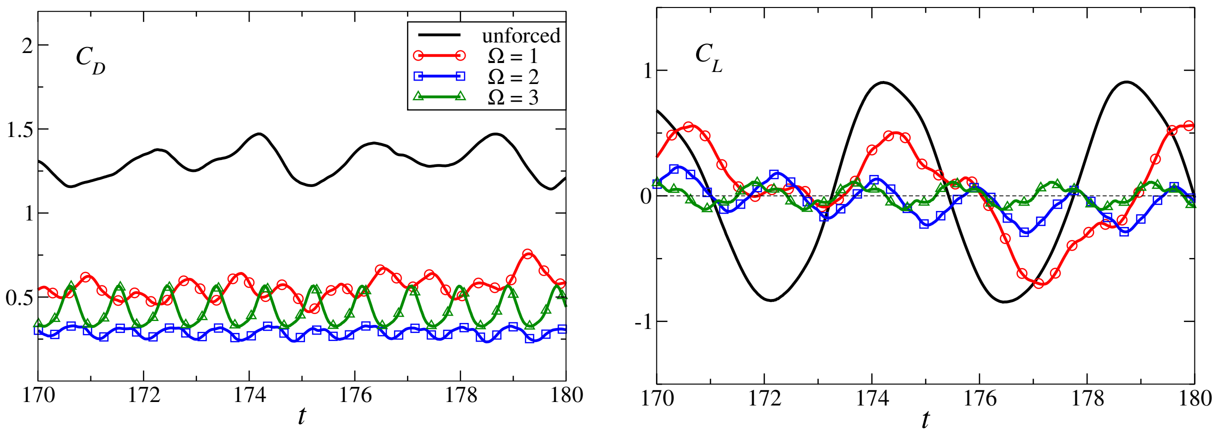

Figure 3. Drag (left) and lift (right) coefficients for simulations with various Ω and f.

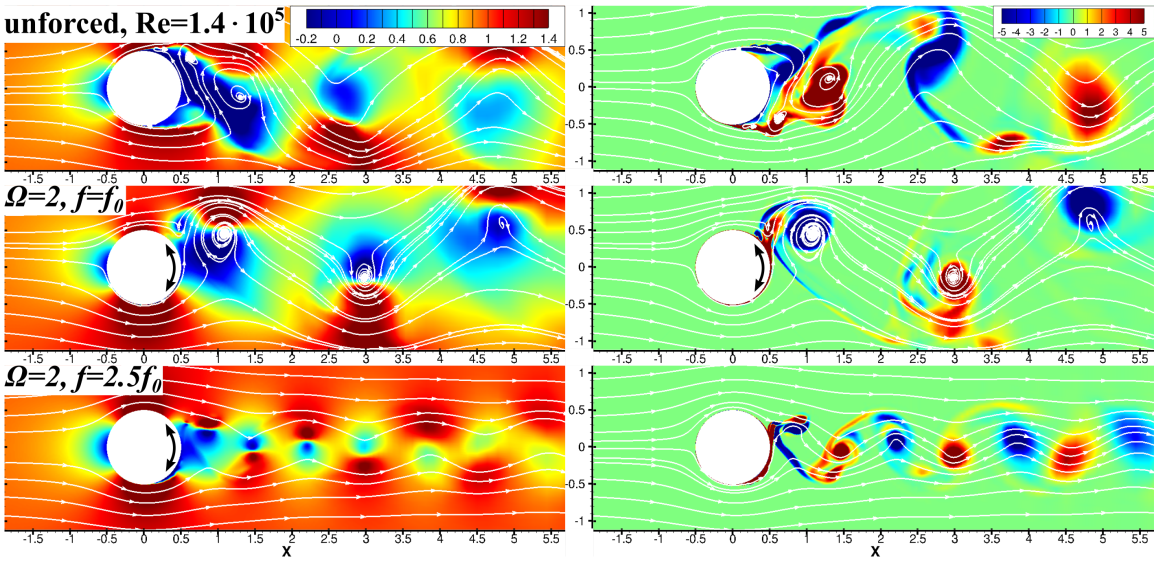

Figure 4. Axial velocity (left) and z-vorticity (right) for simulations with various Ω and f.

rotation in order to determine the optimal parameters when the drag and lift coefficients are significantly reduced. It was found that the high-frequency oscillations can lead to at least 78% $\overline{C}_D$ reduction in comparison with the non-rotating case. Future work will focus on a wide range $\Omega - f$ parameteric study for a complete optimization map.

Acknowledgments

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