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Egor Palkin, Rustam Mullyadzhanov, Muhamed Hadziabdic, and Kemal Hanjalic

Active Heat Transfer and Flow Control over a Cylinder by Rotary Oscillations

Egor Palkin,[1, 2, a)] Rustam Mullyadzhanov,[1, 2, b)]
Muhamed Hadziabdic,[3, c)] and Kemal Hanjalic[4, 5, d)]

[1)] *Institute of Thermophysics SB RAS, Lavrentyev ave. 1, Novosibirsk 630090, Russia*
[2)] *Novosibirsk State University, Pirogov str. 2, 630090 Novosibirsk, Russia*
[3)] *International University of Sarajevo, Hrasnicka cesta 15, 71210 Ilidza, Sarajevo, Bosnia and Herzegovina*
[4)] *Delft University of Technology, Bld. 58, Van der Maasweg 9, 2629 HZ Delft, Netherlands*
[5)] *University of Sarajevo, Vilsonovo setaliste 8, 71000 Sarajevo, Bosnia and Herzegovina*

[a)] *Electronic mail: palkinev89@gmail.com*
[b)] *Corresponding author: rustammul@gmail.com*
[c)] *Electronic mail: muhamed.hadziabdic@gmail.com*
[d)] *Electronic mail: khanjalic@gmail.com*

Abstract. The paper provides a brief overview of recent computational studies of flow and heat transfer control by rotary oscillations of an infinite circular cylinder at a relatively broad set of imposed frequencies and amplitudes [1, 2]. A study for a previously unreachable high subcritical Reynolds number $Re = 1.4 \times 10^5$ showed that the efficiency of this control method increases with *Re* concerning the issue of drag and lift reduction. High-frequency oscillations even lead to around 90 % reduction of the drag. However, the benefits for heat transfer enhancement is not that obvious as the bulk Nusselt number shows only small variations. At the same time its angular distribution around the cylinder becomes much more homogeneous due to oscillations which practically can prevent local overheats.

INTRODUCTION

Most flows regimes over bluff bodies feature a natural unsteady quasi-periodic vortex shedding forming the well-known Karman vortex street [3]. A circular cylinder is often selected as the model problem featuring complex physics of separated flows [4, 5]. Strong unsteadiness leads to the quasi-periodic drag and lift forces acting on the cylinder, meaning that possible scenario of undesired events include vortex-induced vibrations [6]. To manipulate the flow characteristics one typically applies relevant control schemes. The goal may be to influence the shedding mechanism or thermal boundary layer, alternate the drag and lift forces and enhance or suppress the heat flux from the surface. Control methods can modify the flow characteristics by applying various geometry modifications like roughness [7], grooves [8], splinter plates [4], or affecting boundary layer directly with hydrophobic layer on the surface of the object [9], boundary layer suction or blowing [10], or by other means like electromagnetic field forcing [11], inline or transverse oscillations [12, 13] etc.

Rotary oscillations of the cylinder with an optimal rotary oscillation frequency and amplitude can lead to a significant drag reduction by intensive redistribution of pressure azimuthal profile. For instance, the drag reduction of 85 % was previously achieved in experiment for $Re = 1.5 \times 10^4$ [14]. Later this result was qualitatively reproduced for a wide range of rotary amplitudes and frequencies by a two-dimensional [15] and three-dimensional numerical simulations [16], although drag reduction obtained at the optimal parameters was 53 %. Recently we extended these findings to higher $Re = 1.4 \times 10^5$, which is at least one order of magnitude higher which was considered in previous studies. It was demonstrated that this control technique is more efficient at higher Reynolds numbers within subcritical flow regime [1]. However the effect of this method on the heat transfer is not straightforward [2], but allows to reduce local overheats.

PROBLEM FORMULATION

We study an air flow with the incoming uniform velocity U_0 over a circular cylinder of the diameter D. The Reynolds number of the flow is $Re = U_0 D/\nu = 1.4 \times 10^5$ where ν is the kinematic viscosity. The key characteristics are the drag and lift coefficients representing the non-dimensional drag and force values defined as:

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$$C_D = \frac{F_D}{\rho U_0^2 D}, \qquad C_L = \frac{F_L}{\rho U_0^2 D},$$

where ρ, F_D and F_L - the density of the air flow, drag and lift forces acting on the cylinder, respectively.

The heat transfer was also considered for the imposed constant heat flux on the surface of the cylinder. The Nusselt number is defined as:

$$Nu = \frac{Re\ Pr\ q_w}{U_0\,[T_w - T_0]}$$

where $Pr = 0.71$ is the Prandtl number, q_w denotes the heat flux while T_w and T_0 are the temperature at the surface of the cylinder and at the inflow. We impose rotary oscillations by applying a tangential velocity U_w on the cylinder wall as:

$$U_\theta^w(t) = \Omega(t)U_0, \qquad \Omega(t) = \Omega\ sin(2\pi f_e t),$$

where Ω, f_e and t are the non-dimensional amplitude, frequency of imposed oscillations and time, accordingly, normalized with D and U_0. Further we use the ratio $f = f_e/f_0$ normalized by the natural shedding frequency f_0 at considered Re. We analyse the data from a set of URANS simulations of the described configuration obtained using an open-source unstructured finite-volume computational code T-Flows [17, 18]. The wall-integrated Reynolds-stress model [19] is employed on a mesh containing 2.24×10^6 hexahedral cells corresponding to a rectangular domain of the size $L_x \times L_y \times L_z = 25D \times 20D \times 2D$ along the streamwise, vertical and spanwise direction, respectively. The computed cases with imposed rotary oscillations cover a wide range of parameters, i.e. a non-rotating cylinder as well as $f = 1-5$ for $\Omega = 1-3$. An extensive validation of the flow field and heat transfer is presented in [1, 2, 20]. All simulations were performed on $Re = 1.4 \times 10^5$ with URANS RSM [19] model, time-averaged data and instantaneous data were validated against LES simulations with dynamic subgrid-scale model [21] for few selected parameters of rotary oscillations.

RESULTS

To visualize the flow changes imposed by rotation, Fig. 1 shows the isosurface of the Q-criterion for a non-rotating case and $\Omega = 2$, $f = 2.5$. While the flow over a stationary cylinder produces three-dimensional coherent structures and a relatively wide wake, the rotation suppresses three-dimensional evolution of large-scale structures and enforces the Karman vortex street, keeping the rolls almost two-dimensional. To highlight the influence of oscillations on the drag and lift coefficients we show Fig. 2 where the evolution of C_D and C_L in time for $f = 2.5$ and different Ω is presented. Compared to a non-rotating case the drag significantly drops already for $\Omega = 1$. Further increase of the amplitude leads to nearly sinusoidal signal corresponding to a quasi-laminar flow. Figure 3 shows how the drag and lift coefficient vary in the $\Omega - f$ plane. A significant reduction occurs for $f > 1$. With a further increase of frequency, C_D continues to decrease but at a slower pace. There is a notable difference in the drag reduction for different rotational amplitudes. The highest decrease of C_D occurs for $\Omega = 2$ and the lowest for $\Omega = 1$, while for $\Omega = 3$ it falls in between, but closer to the C_D values for $\Omega = 1$.

The distribution of the time-averaged Nusselt number $\langle Nu \rangle (\theta)$ around the cylinder is shown in Fig. 4 demonstrating two distinguished peaks for most cases, at the front and at the rear central points of the cylinder. The bulk Nusselt number varies within 10 % for all cases. For the non-rotating case the rear of the cylinder $\langle Nu \rangle (\theta = 180^\circ)$ is higher than the value at the front ($\theta = 0^\circ$) which is typical for high Reynolds number flow. The front $\langle Nu \rangle$ is the result of a thin laminar boundary layer formed by impingement which grows as the air moves around the cylinder causing a decrease in local $\langle Nu \rangle$. The lowest value is reached approximately at the initial separation point θ_{sep}. The turbulent flow influences the heat transfer in the back of the cylinder ($\theta = 180^\circ$) and it is primarily defined by alternately shed large-scale vortical structures. The circumferential $\langle Nu \rangle$ profile becomes more homogeneous. This feature can be used to suppress local overheats in practical applications.

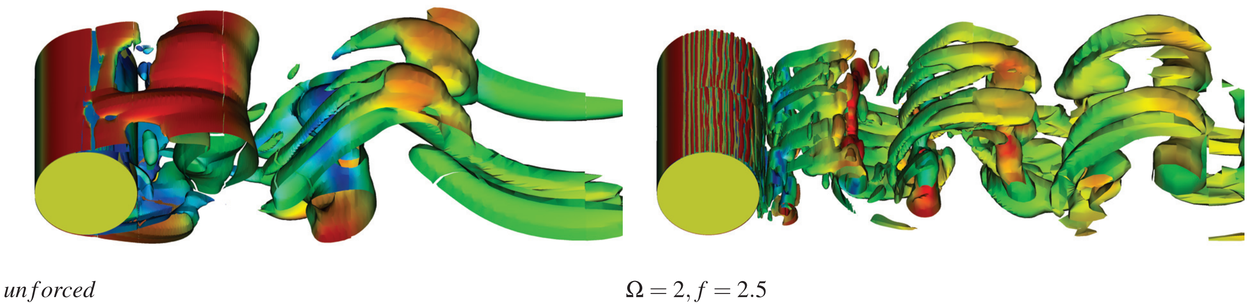

FIGURE 1. Isosurface of $Q = 0.5$ for non-rotating case (left and $\Omega = 2, f = 2.5$ (right) coloured with instantaneous streamwise velocity.

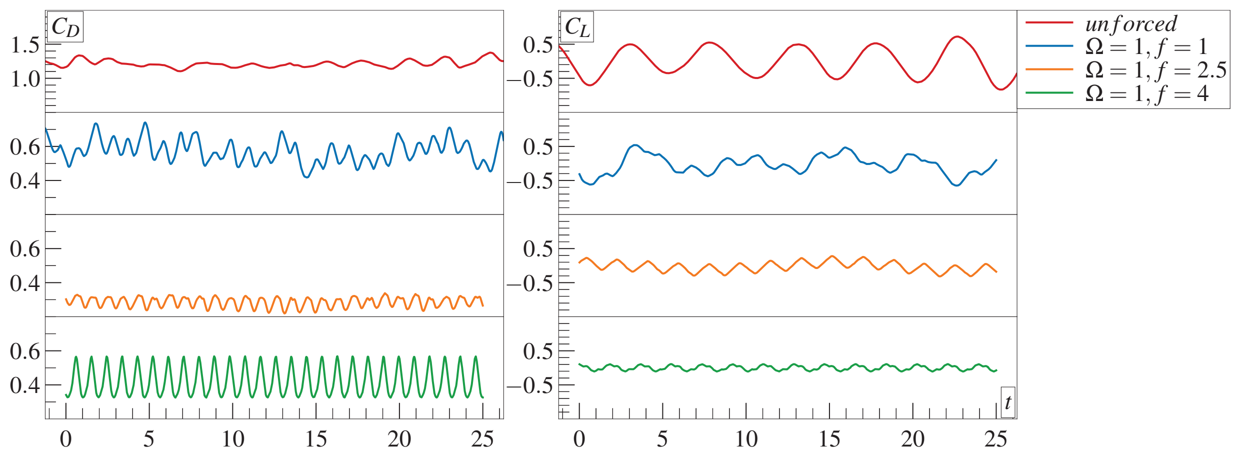

FIGURE 2. (a) Drag and (b) lift coefficient against time for the frequency $f = 2.5$.

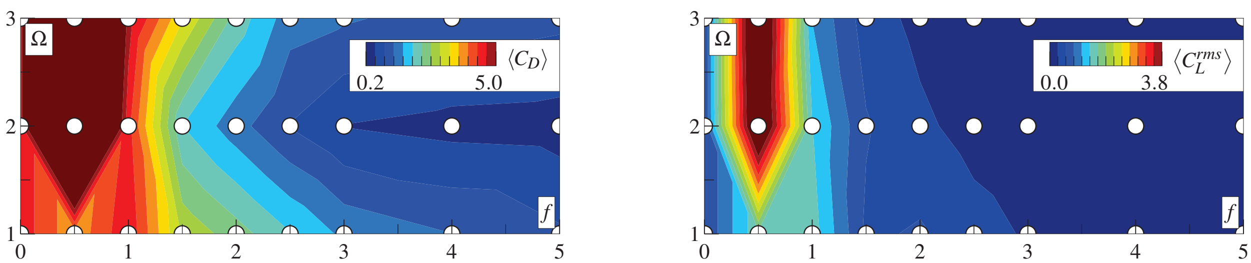

FIGURE 3. The time-averaged $\langle C_D \rangle$ and C_L^{rms} map in the $f - \Omega$ plane.

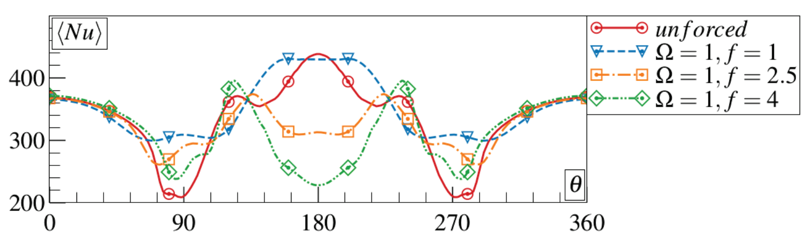

FIGURE 4. Circumferential distribution of $\langle Nu(\theta) \rangle$ for considered cases: the stationary cylinder, $\Omega = 1, f = 1$, $\Omega = 1, f = 2.5$, $\Omega = 1, f = 4$.

CONCLUSION

We provide a brief overview of recent computational studies of flow and heat transfer control by rotary oscillations of an infinite circular cylinder at a relatively large set of imposed frequencies and amplitudes [1, 2]. A study on a previously unreachable high subcritical Reynolds number $Re = 1.4 \times 10^5$ showed that the efficiency of this control method increases with *Re* concerning the issue of drag and lift reduction. High-frequency oscillations even lead to around 90 % reduction of the drag. However, the benefits for heat transfer enhancement is not that obvious as the bulk Nusselt number shows only small variations. At the same time its angular distribution around the cylinder becomes much more uniform due to oscillations which practically can prevent local overheats.

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