Three-Dimensionalities Of The Flow Around An Oscillating Circular Cylinder

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Abstract. Direct numerical simulations with spectral element method of the three-dimensional flow around an oscillating circular cylinder are carried out in Reynolds numbers of 200 to 500, in steps of 100. For that, simulations of imposed body oscillations are realised for low amplitude of oscillation, $A/D = 0.4$, where A is the amplitude of oscillation and D is the circular cylinder diameter, and for high amplitudes, $A/D = 1.0$. As the intention is to analyse the amplitude influence in the wake, the frequency of oscillation is fixed and chosen to be inside the lock-in region, $0.95 f_s$, where f_s is the Strouhal frequency. The three-dimensional wake characteristics of the oscillatory body simulations are compared to the fixed body. The wake vorticity field is used to such comparison as well as the vortical structures identified using the λ_2-definition [6]. Wake characteristics differ with the amplitude. The high amplitude of oscillation triggers a different three-dimensional mode of the wake due to a change in the vortex emission pattern.

Key words: wake three-dimensionality, DNS, bluff-bodies, incompressible flow.

1. Introduction

Vortex-induced vibration plays a major role in structures undergoing currents, such as off-shore structures. Intending a better comprehension of such phenomenon, the forced oscillating cylinder has been studied due to a practical advantage over free oscillations in the possibility of varying the amplitude and frequency at will. Some features of the flow around a circular cylinder in forced oscillations are also present in free oscillations. We started our work with forced oscillations to study the three-dimensional wake in a simpler approach.

Three-dimensional aspects of the wake of a fixed circular cylinder were studied and published. Williamson [9] proposed a classification of the three-dimensionalities triggered at low-Reynolds, modes A and B. These three-dimensionalities are also present in the wake of an oscillating circular cylinder, but other modes also arise seemly due to the asymmetrical vortex emission pattern in certain amplitudes of oscillations. Floquet stability analysis can detect such instabilities as was performed previously by Barkley and Henderson [1] identifying the wavelength of these three-dimensionalities for a single fixed cylinder.

Two-dimensional simulations of an oscillating circular cylinder using discrete vortices method were realised by Meneghini and Bearman [7]. They simulated in a frame of reference fixed to the body imposing an oscillating cross-flow. They obtained the lock-in boundary and presented estimation of the vortex formation length for different values of amplitude and frequency as well as different vortex emission patterns. With intention to further this work, we present three-dimensional structures

of the wake. These situations were also simulated with spectral element methods by Blackburn and Henderson [3].
Inferring at low Reynolds number the role of three-dimensionalities in the wake of a circular cylinder in forced oscillatory flow, we intend to show that different three-dimensionalities are triggered oscillating circular cylinder flow simulations.

2. Results

Aiming a consistent comparison with oscillating body cases and since fixed circular cylinder wakes are well studied, we present a snapshot of the vortex structures, identified using the λ_2-definition proposed in [6], for a fixed circular cylinder in Fig. 1.
It is expected that, from these observations of the lift coefficient in respect to the body movement, changes occur to vortex emission instant. As in many works [2, 7, 4], the phase of the lift coefficient in respect to the oscillatory displacement is associated to the lift coefficient amplitude.
In the three-dimensional simulations we observed that not only the instant of vortex emission has changed,but also the wake characteristics. For instance, the case $Re = 200$ and $A/D = 0.4$ has essentially a two-dimensional vortex street (see Fig. 2(a); the two-dimensional flow resulted is corroborated by Gioria, Carmo and Meneghini [5]. This is strikingly different from what is observed for a fixed cylinder case, where mode A is fully developed for this Re (see the vortex structures in Fig. 1(a)). If only the wake structure was being considered, it would be expected a greater lift force coefficient amplitude for the case $A/D = 0.4$, since the vortex emission is synchronised all along the spanwise direction.
Conversely, when $Re = 300$, the case $A/D = 0.4$ presents essentially the same wake characteristics as the fixed cylinder case. The vortex structures observed in the three-dimensional simulations are very similar (see Fig. 1(b) and Fig. 2(b)). They show the three-dimensional structure of mode B, which is the dominant mode for this Re.
In respect to vortex emission modes classification proposal by Williamson in [10], all low amplitude cases wakes resembled the fixed cylinder one: there is a von Kármán *2S* wake, as seen on Fig. 3(a)-(d).
For $Re = 200$, the increase of amplitude leaded to a change in the vortex emission pattern, which was *P+S* in this case, see Fig. 3(e). In addition, the three-dimensional features of the wake were also altered. A small wavelength three-dimensional instability, of $L_z \simeq 0.84D$, appeared for $Re = 200$, which could be provoked by the increase in the velocity of the flow relative to the body due to the cylinder oscillation, i.e., an increase in the "local Re", Fig. 4(a). However, the small wavelength instability in this case is not mode B, it is of mode C, with a period doubling nature as in Fig. 5(b). In other words the instability has a period of twice the period of the base flow. Mode C has also been observed in some asymmetrical wakes in bluff body flows, as documented in [11] and [8].
As already indicated by the wavelength of three-dimensional structures seen in Fig. 4(a), mode C is the dominant mode when three-dimensional simulations are carried on. Its period doubling is remarkably different from mode A, which is observed in the fixed cylinder case illustrated in Fig. 5(a). In this figure, it can

be seen that the same streamwise vorticity pattern is repeated from cycle to cycle, without changing sign.

For higher Reynolds number cases, the simulations present a wake vortical structure with a slightly shorter wavelength, see Fig. 4(b) to Fig. 4(b), although it does not present a different three-dimensional mode like $Re = 200$ case. This corroborates that the trigger to mode change is the presence asymmetrical wakes.

In respect to the vortex emission pattern, as referred before, the only pattern that is not symmetric occurs for $Re = 200$, see Fig. 3, which presents a *P+S* pattern. When Reynolds number is higher, the vortex emission pattern is a symmetric one, *2P*. See Fig. 3, this is very clear when Reynolds number is 300 and 400, and not so clear when $Re = 500$.

3. Conclusions

Modifications in the wake features for cases of low Re and high amplitudes were expected, since the body experiments considerable instantaneous velocity in such cases, thus substantially increasing the instantaneous Re. Due to the asymmetry of the P+S wake present in these cases, the appearance of mode C is not surprising [8]. The wake topology and period-doubling nature found for this mode are also found in DNS realised in this work, but the spanwise wavelength seems different (see [5] for Floquet mode obtained for this case).

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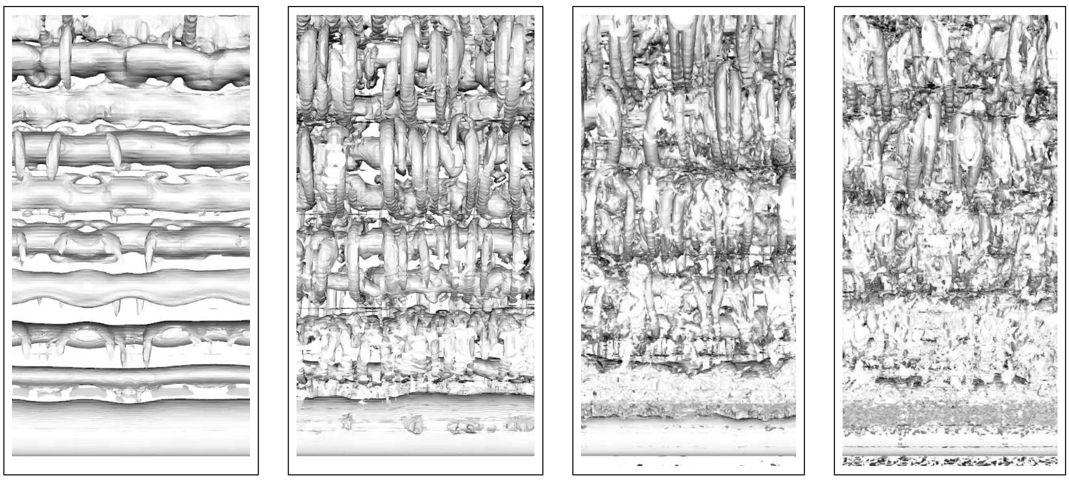
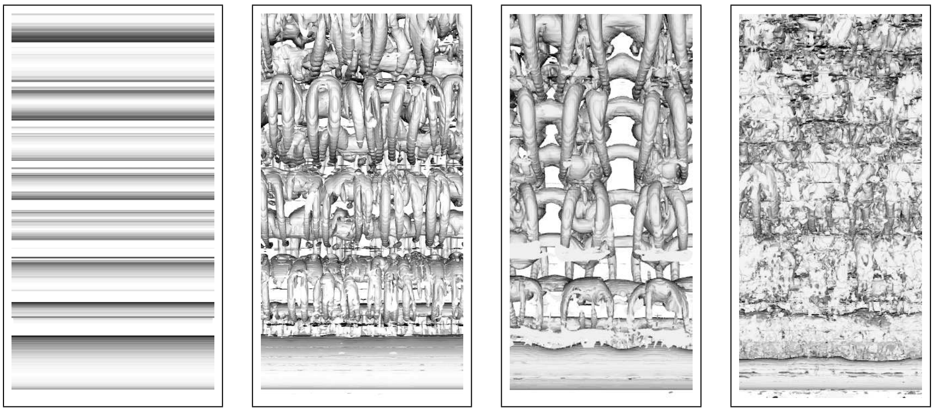


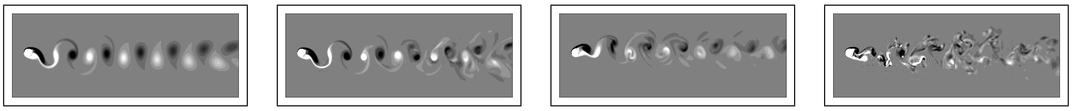
(a) $Re = 200$. (b) $Re = 300$. (c) $Re = 400$. (d) $Re = 500$.

Figure 1. View of vortex structure for fixed circular cylinder cases.

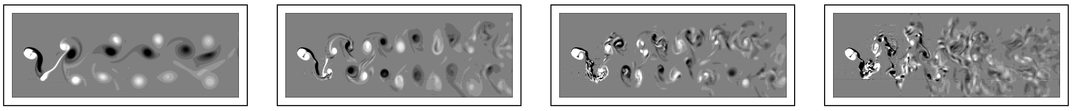


(a) $Re = 200$. (b) $Re = 300$. (c) $Re = 400$. (d) $Re = 500$.

Figure 2. View of vortex structure for forced oscillating circular cylinder with amplitude $A/D = 0.4$.

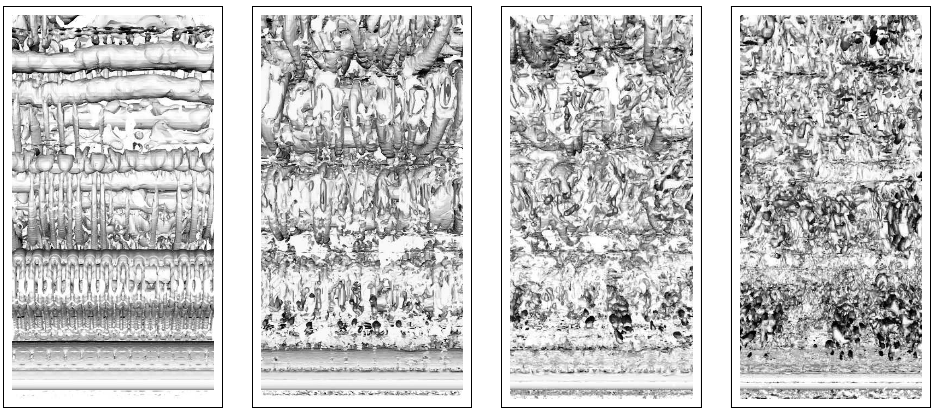


(a) $Re = 200, A/D = 0.4$. (b) $Re = 300$. (c) $Re = 400$. (d) $Re = 500$.



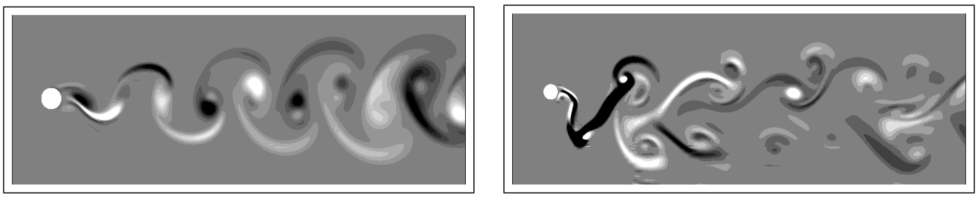
(e) $Re = 200$. (f) $Re = 300$. (g) $Re = 400$. (h) $Re = 500$.

Figure 3. Contour xy slice at cylinder midsection of instantaneous vorticity in z-direction (ω_z) for oscillating circular cylinder. (a)-(d) with amplitude $A/D = 0.4$ and (e)-(h) with amplitude $A/D = 1.0$. Vorticity ω_z levels from black, -2, to white, 2.



(a) $Re = 200$. (b) $Re = 300$. (c) $Re = 400$. (d) $Re = 500$.

Figure 4. View of vortex structure for forced oscillating circular cylinder with amplitude $A/D = 1.0$.



(a) $Re = 200$, fixed. (b) $Re = 200$, $A/D = 1.0$.

Figure 5. Slice along cylinder centreline of instantaneous vorticity in x-direction (ω_x), flow direction. Vorticity ω_x levels from black, -0.5, to white, 0.5.

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