Computational Study of 2D Flow Past a Circular Cylinder Oscillating Transversely to Incoming Flow

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1 Introduction

In structural, offshore, and thermal power engineering disciplines, the correlation within the movement of circular cylinder and the inconsistent wake of a round cylinder in a cross-flow is critical [1, 2]. In cross-flow oscillations, one important thing about the cylinder–wake interaction phenomenon is the position in the flow cycle (where vortices form and break apart) depends on the frequency of oscillation of the circular cylinder.

The duration of vortex formation (evaluated concerning circular cylinder vibration) needs to switch phase by about 180° for a significantly narrow spectrum of forced oscillation frequencies, according to observations by Ongoren and Rockwell [3]. The above sensitivity is demonstrated for flows in which the frequency of the circular cylinder in cross-flow oscillation (fo) is similar to the natural shedding frequency of the fixed cylinder (fv). The research suggests that, at least for low vibration amplitudes, the vortex-shedding behavior on both sides of a switch is identical to the normal Karman-street wake. The switch can also change the direction of mechanical energy transmission among the vibrating cylinder and the flow as well as the phase of strains caused by vortices on a cylinder.

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Koopman [1] studied flow visualization of forced transverse excitation at various amplitude ratio values and found that the lock-on range is adapted to greater DA. Up to DA 5, Williamson and Roshko [4] explored the impact of high amplitude ratio values on the wake. They identified a variety of unusual wakes and designated them with numbers and letters that reflected the mixture of duos of single vortices (S) shed and vortices (P) shed within one cycle of forced oscillation. Using the k-epsilon model, Hines and Thompson [5] investigated the turbulent flow over a square cylinder with specified motions. Moreover, the anticipated lock-on region is substantially greater than the findings of other researchers. In comparison to cross-flow-forced excitations, experimental investigations of inline forced cylinder oscillations are rather rare. This is because the cylinder is subjected to a smaller stream-wise fluctuating force F_x, which is just one-tenth the size of the transverse varying force F_y [6].

The current study focuses on a detailed computational analysis of the cylinder–wake interaction behavior for a single oscillation amplitude, but over a wide range of frequencies near the fixed cylinder's vortex shedding frequency. The *Re* was established large enough to observe the occurrence of switch behavior at the utilized amplitude of oscillation. The constraint to a single amplitude, *Re*, as well as 2D flow simulations, were done so as to keep the requirement on computational assets to a minimum meanwhile still producing invaluable information.

2 Literature Review and Objective

The purpose of this research is to see how changes in frequency ratio $F = f_{\mathrm{e}}/f_{\mathrm{so}}$ affect entrainment characteristics caused by forced cross-flow oscillation in the main synchronization scheme. Our estimates are only limited to 2D flows with a low Reynolds no. as well as Reynolds numbers of 500 and 1000 with a natural frequency of circular cylinder at $Re = 500$ and 1000 being 0.573 and 1.3, respectively. Furthermore, to lessen the strain on computational system, the analysis is limited to a single cross-flow oscillation at an amplitude ratio of $A/D = 0.02$.

The relevance of 2D solutions for this challenge requires some clarification. The wake of a stationary cylinder is 3D and chaotic at $Re = 500$. Past studies have shown that span-wise association of forces, wake velocities, and other variables increases with increasing amplitude of cylinder motion or oscillation [7–12]. It is fair to conclude that the harmonic motion of a long circular cylinder suppresses 3D nature and produces flows that are more 2D than fixed circular cylinder equivalents, at least in the near-wake zone.

This has been established that forcing a cylinder to oscillate at modest amplitudes can postpone the advent of 3D in its wake. For R_{e} up to 300–400, Koopman [1] and Griffin and Ramberg [13] established that the wake was virtually 2D at vibration amplitudes beyond 10% of the cylinder diameter. Berger [14] demonstrated that regulated oscillations could stable and extend a laminar vortex-shedding regime to $Re = 350$–300 in experimental research. The span-wise relation of the wake street is improved with $Re = 1000$ and $A/D = 0.05 < 0.125$; however, the vibration is not powerful enough to completely inhibit the 3D instability.

3 Materials and Methods

Quadrilateral cells were used throughout to achieve discretization. The no-slip wall boundary criteria were used to specify the cylinder's surface. To accomplish pressure–velocity coupling, the incompressible Navier–Stokes equations were resolved utilizing a second-order unsteady solver methodology using the software ANSYS FLUENT 2021, along with the combination of SIMPLE approach. The circular cylinder in Fig. 1 has a diameter of $D = 0.05$ m, which represents a standard domain employed in the investigation.

A user-defined function (UDF) was utilized to create cylinder's oscillating motion. Furthermore, oscillation orientation, frequency of excitation, and amplitude determine the cylinder's specified motion. Consider the motion of a circular cylinder driven to oscillate in response to an incoming flow field, as shown in Fig. 2. The amplitude is A and the cylinder's path at any time (t) is $\xi(t)$.

$$(t) = A\sin[2\pi f_{\mathrm{e}}(t - t_0)], \tag{1}$$

where t_0 is the time delay in this investigation. As orientation in this study is transverse $(\alpha = 90°)$. For $\alpha = 90°$, $x(t) = 0$ and $y(t) = A\sin(2\pi f_{\mathrm{e}} t)$, a UDF was utilized to create the cylinder's oscillating motion with whole cells of mesh being updated following each time step with the help of dynamic mesh model.

a. *Mesh independence*

For mesh refinement investigation, three meshes were created. The force coefficient along the x-axis (C_x), Strouhal number (St), and peak-to-peak readings of the

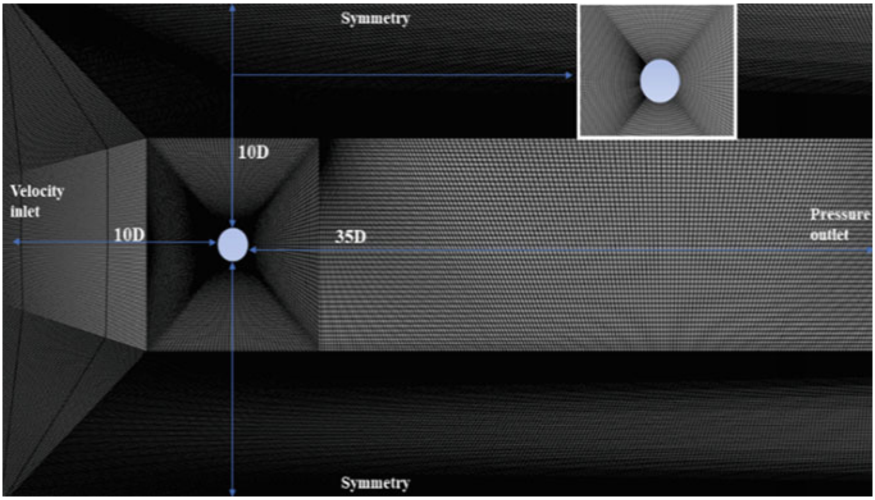

Fig. 1 Schematic of mesh distribution in a 2D computational domain

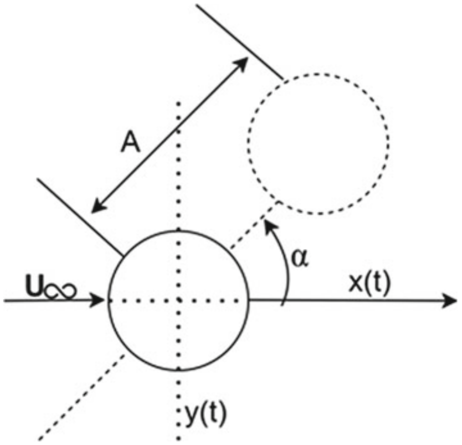

Fig. 2 Schematic of circular cylinder oscillating at an angle α to flow field

force coefficient along y-axis (C_y), along with the specifics of the meshes, are all compared in Table 1. The given produced readings of fluid flow across an oscillating circular cylinder were for $Re = 500$. With the improvement of meshes, the difference between the solutions reduces, and grid independence is attained. Then, Mesh 2 was selected for further calculations. The increase in the number of nodes for meshes is considered to be ~ 20,000. The primary flow properties were compared and found to be in excellent endorsement with published information.

b. ***"P + S" vortex-shedding modes***

The confirmation was required in the provision of two "exotic" vortex-shedding modes to achieve better assurance in the CFD analysis using Ansys. The first wake mode to be verified was P + S, which denotes the vortex pair continued by a single vortex shed in one oscillation period [4]. The oscillation of cylinder was transverse at *Reynolds no* $= 500$, $A/D = 0.02$, *and* $F = f_e/f_{s0} = 0.875$ *in this instance.* Figure 3 depicts the comparison of P+S mode for cylinder as given in present study with Blackburn and Henderson [15] which utilized the discrete-vortex approach with viscous diffusion. The P + S configuration bears a strong resemblance to every one of the

Table 1 Comparison of drag and lift coefficient with published data, Blackburn et al. [15], $A = 0.25$, F (f_e/f_{s0}) $= 1.0$, $Re = 500$

Mesh	Total nodes	Sf	Cl	Cd
Mesh 1	56,605	0.195	1.335	1.531
Mesh 2	71,965	0.223	1.735	1.429
Mesh 3	91,440	0.216	1.651	1.445
Blackburn et al. [15]	–	0.228	1.776	1.414
% Error (compared with Mesh 2)	–	2.19	2.3	1.06

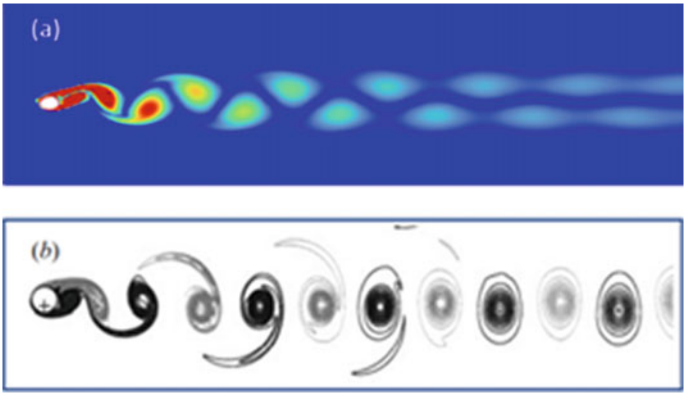

Fig. 3 P + S mode comparison for circular cylinder at $Re = 500$, $A/D = 0.02$, $F = 0.875$: **a** present investigation: **b** Blackburn and Henderson [15]

two analyses. The present simulation also shows the vortex pairs rotating clockwise as they go downstream, which is consistent with Blackburn and Henderson's [15] simulation. They also discovered that the flow under this situation had some "memory," even though the vortex-shedding pair's part was dependent upon the circular cylinder's beginning orientation. Additionally, this outcome of memory is validated within the present investigation, though not displayed herein.

4 Results and Discussion

The examination of a circular cylinder's wake is significant when it oscillates due to to self-excitation. In addition, the physics of wake formations can be best defined. As a result, numerical simulations were performed for a diverse combination of excitation frequencies (f_e/f_{s0}) ranging from 0.76 to 1.02 and amplitude of vibration a/d fixed to 0.02 and for the low Re as well as $Re = 500$ and $Re = 1000$.

4.1 Lock-in Boundary at Re = 500 and Re = 1000 and A/D = 0.02 with A = 90° (Transverse Oscillation)

The "lock-in" boundary or the "synchronization regime" is developed by examining the types of reactions to a different excitation frequency. A phase plane graph is a plot that shows the relationship between each and every two domain state vectors across time. In this scenario, the velocities across the X-direction (U_x) and Y-direction (U_y) of the stream fulfill this objective. In short, Fig. 5 simply shows the effect of excitation frequency at a constant vibration amplitude (a/d) of 0.02.

For *Re* = 500

For $F < 0.8$ with $Re = 500$, the phase plane, C_d and C_l, can be observed in quasi-periodic regime. According to Fast Fourier transforms, the time series of lift exhibited substantially spiked spectral characteristics, including two major frequency responses. Meneghini et al. (as seen in Fig. 9a) [16] show identical trend at $Re = 200$ discrete-vortex numerical simulation outcomes at $F = 0.75$, $A = 0.25$. For $f_e/f_{s0} = 0.8$, though, the chaotic phase plane disappears and is replaced by a single, stable periodic orbit which is referred to as the "limit cycle."

For F in between 0.905 and 0.95, the existence of two fundamental, incommensurate frequencies characterized in accordance with the weakly chaotic zone has been reported: One is at the frequency of the cylinder oscillation, whereas the other results from a nearly periodic switching between waking phases. Throughout such regime, the cylinder oscillation frequency and its odd harmonics have steeply peaked spectra in the Fast Fourier transform of lift time series; however, the long-period switching frequency has no discernible spike. Figure 4a shows a time series of Cl for the outcomes calculated under the given domain at $F = 0.94$. The time necessary to switch approaches has been shortened as F has increased. Due to the extraordinarily long periods associated in accordance to the lowest frequency ratios, the precise specifics of the variations in switching periods with F have not been validated.

For $F > 1.016$, Fig. 4b demonstrates the time evolution of C_d (coefficient of drag) and C_l (coefficient of lift) considering flow regime in the chaotic zone (for $F = 1.02$). Moreover, the Fast Fourier transform (FFT) of time series of C_l (Coefficient of lift) shows a dominating, but not very sharp, spike at Strouhal frequency, as well as peaks at its odd harmonics. These characteristics, including the randomness of time series depicted in Fig. 4b, imply the nature of flow as chaotic.

Furthermore, the occurrence of these frequencies could be described using Fast Fourier transforms (FFTs) derived from the data of coefficient of lift, which are also shown in a similar figure. The occurrence of a single distinct spike signifies "lock-on," whereas the hegemony of both frequencies is referred to as "non-lock-on." In Koopman's early investigations [1], a Lissajous figure was seen to determine

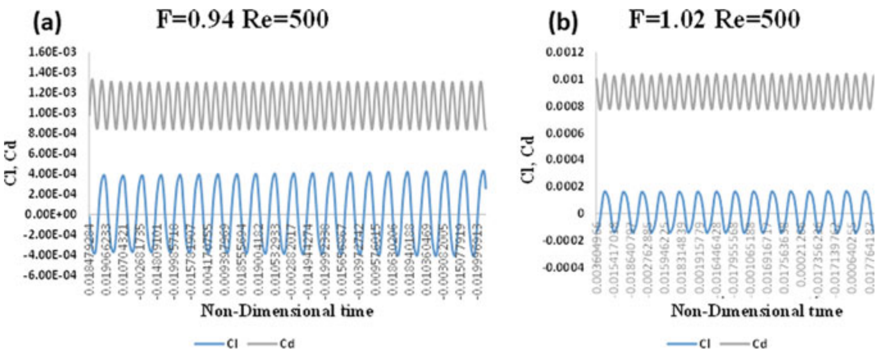

Fig. 4 Time series of C_d and C_l at **a** $F = 0.94$ and **b** $F = 1.02$

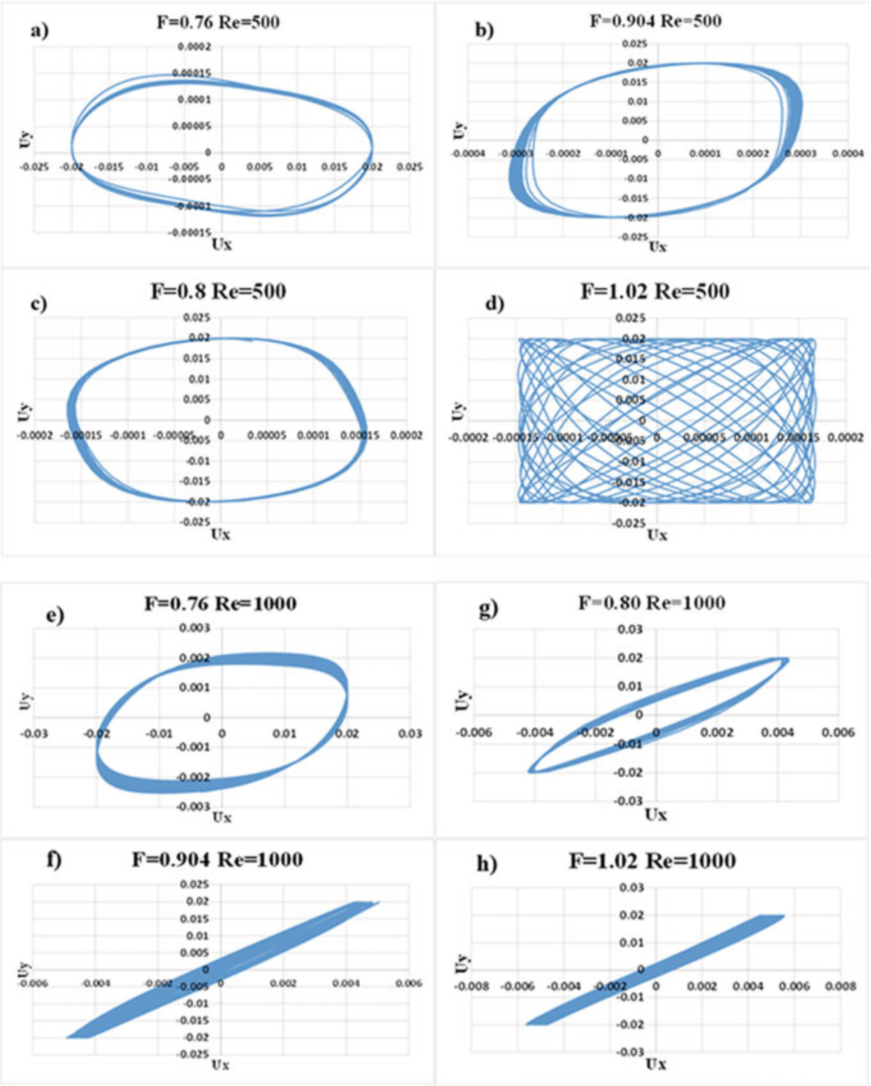

Fig. 5 FFTs and phase plane schematics for oscillating cylinder at $Re = 500$ and 1000

whether the driver oscillator and the hot-wire signal were of the same frequency. Furthermore, whereas the Lissajous figure was displayed as a "steady single loop," the vortex street was called "locked-in." The circular cylinder vibrated at a natural shedding frequency in his investigations. Since this work used a more reliable simulation approach associated with a robust numerical method, the current findings are consistent with the experimental data.

For *Re* = 1000

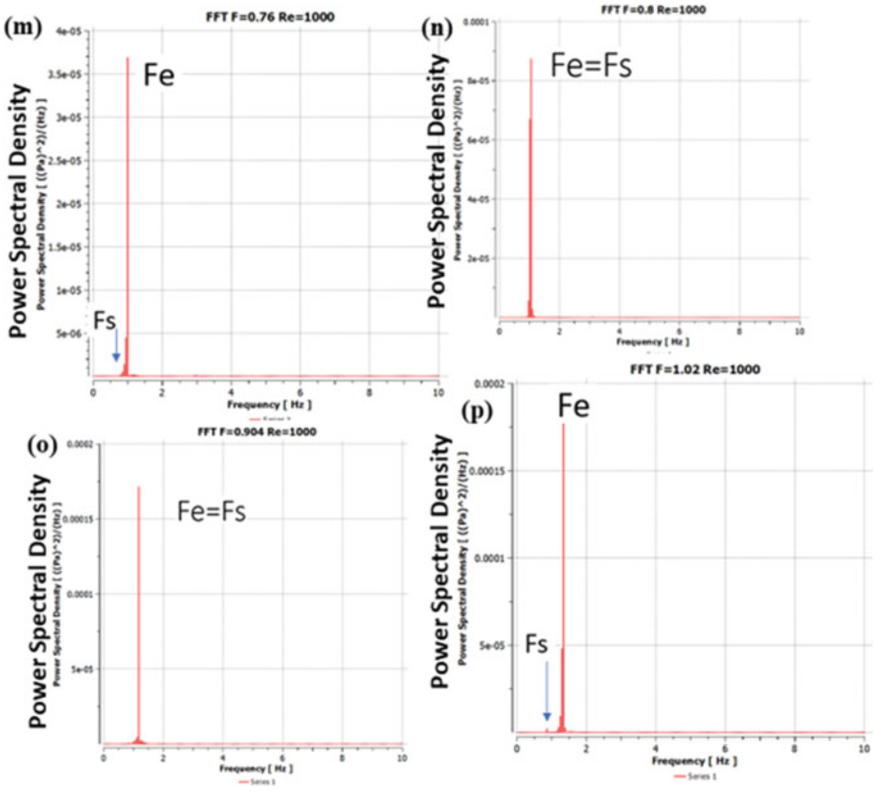

Fig. 5 (continued)

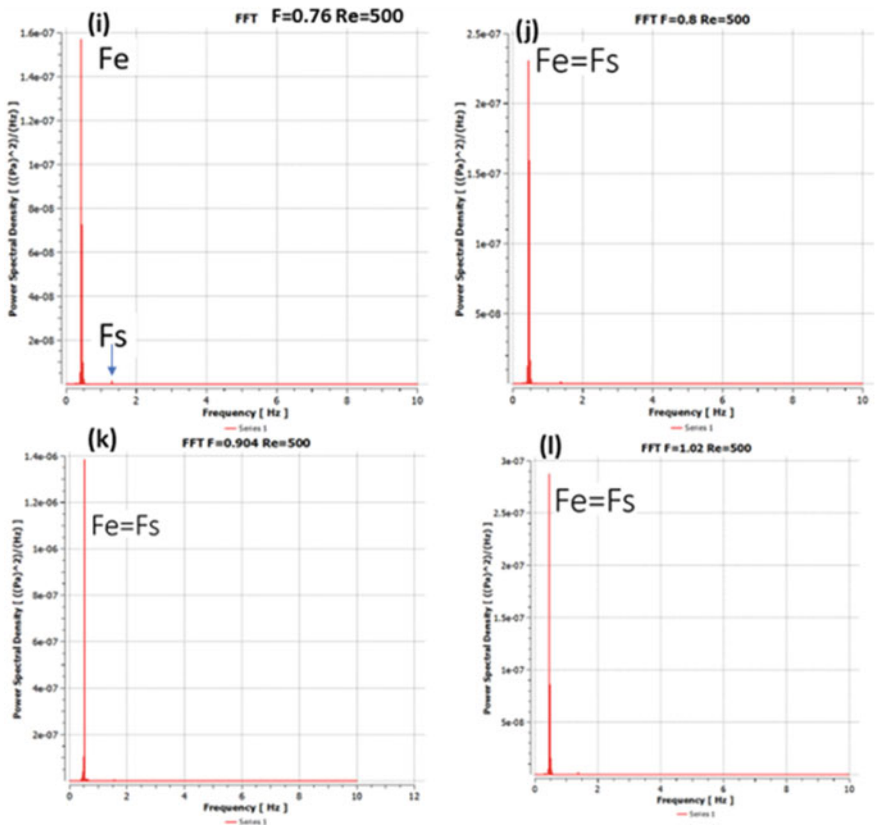

Fig. 5 (continued)

During the instances when $F < 0.8$, the phase plane is visible in unstable periodic courses, and hence, the presence of weakly chaotic zones can be seen. Even so, at $F = 0.8$, it is interesting to observe the weakly chaotic zones converging into a single, stable periodic course. The aforementioned is commonly referred to as a "limit cycle." There is, however, a band during which the frequency of excitation is capable to force the frequency of vortex shedding within its corresponding value, as shown in Fig. 5 where it sustains up to $F = 0.904$. The phase plane once more turns chaotic and aperiodic for $F \geq 1.02$. The Fast Fourier transforms (FFTs) derived from the lift coefficient histories, which are also shown in the very same image, could also be used to demonstrate the origins of these frequencies.

5 Conclusions

The dynamic mesh approach was used to model laminar incompressible flow across a cylinder with a user-defined function (UDF) utilized to create cylinder's transverse oscillating motion to the free-stream flow along with the combination of the SIMPLE approach. This function offers a potent method for modeling a flow past objects. Thorough verification of the simulation's outcomes using "physical" motion across the transverse axis has also produced outcomes that were in accordance with the findings of the existing numerical and experimental studies. The associated excitation and flow parameters also led to the observation of several near-wake vortex shedding phenomena that have been earlier found in several studies. Force amplifications and typical lock-on features, for like $F = 1$, were correctly anticipated.

Some of the findings of the present study are:

- The effect of "phase-lock-on" was extensively proven by plots of Fast Fourier transform, wake structure, phase-plane, temporal drag and lift coefficients, etc.
- A phase plane is uneven, non-periodic, and weakly chaotic in the non-lock-on condition.

Nomenclature

A	Amplitude
St	Strouhal frequency
C_d	Drag coefficient
α	The angle of oscillation of cylinder with respect to incoming flow field
C_l	Lift coefficient
Re	Reynolds no

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