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A CFD Study of Flow Past a Rotating Cylinder to Re = 1000

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Abstract

In this paper, we examine, computationally, a uniform flow past a rotating circular cylinder. The objective is to determine the effect the rotation has on the lift and drag acting on the cylinder, on the vortex structures and on the vortex-shedding frequency. A streakline calculation illustrates the effect the rotation has on the vortex-structure in the wake. A combination of finite-difference and spectral methods is used to calculate the three-dimensional incompressible unsteady Navier-Stokes equations in primitive variable form in nonorthogonal curvilinear coordinates. A second-order accurate in time fractional-step method is used to decouple pressure and velocity components. High-order compact-difference schemes are used to avoid the problem of the so-called checker-board behavior. The calculated lift coefficient (C_L), drag coefficient (C_D) and pressure coefficient (C_P) of the flows at a Reynolds number of 200 and α = 1 to 5 (α is the nondimensional ratio of the rotating speed-to-free stream speed) agreed very well with results in the literature. However, streak line patterns were not presented in these earlier studies. We also have drag and lift results at Re = 1000 for the same range of α values. These results are found to follow the same trends as at Re = 200. These results have a practical application in offshore drilling.

1. Introduction

An offshore drilling concept which involves rotating the drill string in the absence of a stationary external pipe is a possibility for development. This technique exposes the rotating drill string to whatever current is present in the ocean environment at that particular location. The question that arises concerns the effect of the drill string rotation on the vortices being shed from the drill string. How is the vortex shedding being affected the drill string rotation? Is the possibility of the onset of vortex-induced vibration (VIV) affected by the rotation of the drill string? This investigation begins an examination of this possibility.

It is an established fact from fluid dynamics that a rotating cylinder subject to a uniform flow experiences a constant mean force perpendicular to the direction of the flow. This is due to an increased velocity on one side of the cylinder (causing a decrease in pressure), and a decreased velocity on the other side of the cylinder (causing an increase in pressure). This situation is depicted in numerous fluid dynamics textbooks. Such a flow field generates "circulation" around the cylinder. The circulation which leads to the constant mean transverse force, F_T , is given by $F_T = \rho U\Gamma$ where ρ is the fluid density, U is the uniform approach velocity, and Γ is the circulation around the rotating cylinder. This transverse force, F_T, is known as the Magnus force.

In a real fluid situation, the transverse force is represented by an oscillation about the mean due to vortex shedding. This oscillation is clearly shown in the results obtained by many authors; see, e.g., Mittal and Kumar (2003) which will be discussed in more detail later.

This investigation has revealed that there is a dearth of information on the subject of how shed vortices are affected in the case of a uniform past a rotating cylinder, except at low Reynolds numbers. The several studies at Reynolds numbers as high as 1000 have not included any turbulence modeling to represent the actual state of the flow nor have they considered the flow to be three-dimensional. The lack of information on this subject in the open literature makes it difficult to speculate how the vortex structures will be affected by the cylinder rotation at higher Reynolds numbers. The available literature will be examined on the question of how vortex shedding is influenced by the rotation of the cylinder at these lower values of Reynolds number which produce a laminar wake.

The parameters of the physical problem are the Reynolds number based on a constant velocity approach flow and the parameter α which is defined as the velocity of the cylinder at its outer radius divided by the constant approach velocity, $\alpha = D\omega/2U$, where ω is the rotational velocity, D is the cylinder diameter and U is the constant approach velocity. These two parameters are sufficient to describe the physical problem. The Reynolds number could range from a quite small value to a quite large value in the physical application of rotating drilling riser, simply by a decrease in the current velocity past the cylinder. It is noted that for Re ≥ 200, the wake flow past the rotating cylinder is expected to be turbulent. In this paper, the numerical simulation of streak lines at α = 0, 1.0, 1.5, 2.0, 3.0, 4.5 and 5.0 is used to study the flow details around the rotating cylinder. Very distinct flow patterns are found in four different ranges of α values. In the first range (α = 0.5 to 1.5), vortices were shed alternately and periodically from the cylinder, with the amplitude and period of the lift coefficient about the same as for the nonrotating (α = 0) case. As α was increased to the second range (α = 2.0 and 3.0), vortex shedding was completely suppressed, and the flow field achieved a certain steady state. When α was further increased to the third range (α = 4.5), vortex shedding appeared again, however, it was quite different from that in the first α range. First, the vortex was only shed from one position instead of two alternating positions. Besides, the process was much slower. As the value of α further increased to the fourth range (α = 5.0), vortex shedding was suppressed and the flow field again obtained a steady state. These topics will be discussed in more detail later.

2. Relevant Literature

Each of the numerical studies to be discussed considers the flow to be two-dimensional which presents no serious effect on the calculated results. Two-dimensional studies for a constant approach flow tend to over-predict the force coefficients by at least 15-20% when the flow is three-dimensional. The calculated results are presented typically for Reynolds numbers ranging from 200 to 10^3 with a token discussion of results at Re = 10^4. Note that these Reynolds numbers are at least one order of magnitude below the values that would be found in most practical situations. In addition, the wake flow at the Reynolds numbers considered in these papers has become turbulent for Re > 200, although no turbulence modeling was used by any of the references considered herein. The omission of turbulence modeling is considered to be more serious than the assumption of 2-D flow.

The papers that are relevant to this study are briefly summarized in the following discussion: Badr et al. (1990) studied the problem of a rotating cylinder in a uniform flow at Re = 10^3 and α = 0.5, 1.0, and 3.0. The dimensionless time is defined as $\tau = 2\ Ut/D$, t is the physical time and the other terms have been identified earlier. The numerical study of Badr et al. is done using what appears to be a Fourier series expansion method. This could be a Direct Numerical Solution, but the technique is not sufficiently discussed to be able to tell. Badr et al. carried the calculations to $\tau = 20$. An observation here is that the numerical solution had not converged to a periodic time-dependent solution by τ = 20. It seems that the computational time should have been longer for a periodic time-independent solution to have been obtained. The lift coefficient had not reached an established value, i.e., the starting transient of the numerical solution was still present at τ = 20. Further evidence of the starting transient issue is that the period of oscillation of C_L at α = 0.5 and 1.0 had not reached an established trend. This suggests that the vortex-shedding frequency had not become established. A meaningful and very relevant observation from the α = 3 result is that, for a large enough rotational speed, the vortex shedding effects are completely suppressed because C_L and C_D are experiencing no oscillation.

Chew et al. (1995) used a hybrid vortex scheme to represent the flow past a rotating cylinder at Re = 10^3, with no apparent turbulence modeling which should have been necessary at this Reynolds number. The study of Chew et al. was carried to a dimensionless time of τ = 100 which is adequate to obtain a solution independent of the starting transient. These results showed that the lift coefficient had no oscillations by α = 4, which suggests that vortex shedding had been damped.

Chou (2000) also conducted a 2-D finite-difference study of the rotating cylinder problem at Re = 10^3, 10^4 and $2\text{x}10^4$ for various values of α, also with no turbulence modeling. The pressure-Poisson equation was solved by a Fourier, finite-analytic approach. The calculation is done only to a dimensionless time of 20 which, as with Badr et al. (1990), was not sufficient for the transient effects of starting the calculation to have diminished.

Thus, the results of Badr et al., Chew et al., and Chou have not properly represented the flow at the Reynolds numbers they studied. Mittal and Kumar (2003) examined this problem at Re = 200 and $0 < \alpha < 5$. They found that vortex shedding was suppressed for $1.91 < \alpha < 4.2$ based on the lack of oscillation in the lift coefficient. However, time-dependence reappeared in the lift coefficient for $4.3 < \alpha < 4.7$, but vanished again for $\alpha > 4.7$. Mittal and Kumar noted that there was one-sided vortex shedding in the range $4.3 < \alpha < 4.7$. Mittal (2004) found some three-dimensional influences in the flow compared to the earlier two-dimensional results of Mittal and Kumar for Re = 200 and α = 5. The pressure coefficient at the cylinder shoulder was found to be strongly affected by the aspect ratio; its value ranged from -30 for the two-dimensional case to -12 for an aspect ratio (AR) of 5, -17 for AR=10, and -19 for AR=15. The aspect ratio is the cylinder length divided by the diameter. It is quite likely that this same behavior would be present at higher values of Re and for the values of α in a 3-D flow.

In one of the few experimental studies of the vortex structure for the rotating cylinder, Dol et al. (2007), for Re = 9000 and $0 < \alpha < 2.7$, found that vortex shedding was suppressed for $\alpha > 2$. This is the same result that Mittal and Kumar obtained, but for a much lower value of Re in a two-dimensional calculation. Thus, is clear that additional effort is needed to bring a clearer understanding of how cylinder rotation is affecting the vortex behavior behind a cylinder in a uniform approach flow. In addition, there is a need to examine the development of the single vortex structure as Re is increased.

3. Analysis

The three-dimensional unsteady incompressible governing equations (Navier-Stokes equations) in general coordinates were solved using a combined spectral/finite-difference method. A semimplicit fractional-step method was used to decouple the pressure from the velocity. Large eddy simulation with Smagorinsky subgrid modeling and Van Driest damping was implemented for Re = 1,000. Two-dimensional potential flow was used as the initial condition. A small perturbation was added to trigger the three-dimensional effects for the calculations at Re = 1000. On the cylinder wall, no-slip and no-penetration boundary conditions are applied to the velocity. For pressure on the cylinder wall, a Neumann boundary condition in rotational form was used. On the outer boundary, a convection boundary condition was used for both velocity and pressure. The outer boundary was taken to be 30 cylinder radii from the cylinder. Periodic boundary conditions were applied in both the axial and circumferential directions. For Re = 200, a grid of 384 x 256 with a time step of 0.001 was used. At Re = 1000, a grid of 256 x 192 x 32 was used with a time step of 0.001 was used. Grid convergence of the solution at both values of Re was found.

4. Results

Results have been obtained at the present time for two cases. At Re = 200, the flow is essentially laminar and two-dimensional; hence the calculation was laminar and two-dimensional. At Re = 1000, the wake is turbulent and three dimensional.

We have essentially duplicated the results of Mittal and Kumar (2003) in regard to the lift coefficient at Re = 200 for $0 < \alpha < 5$. Our results are shown in Fig. 1. The C_L

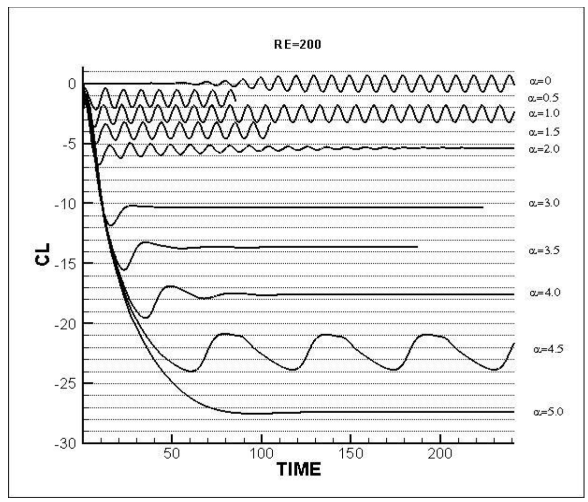
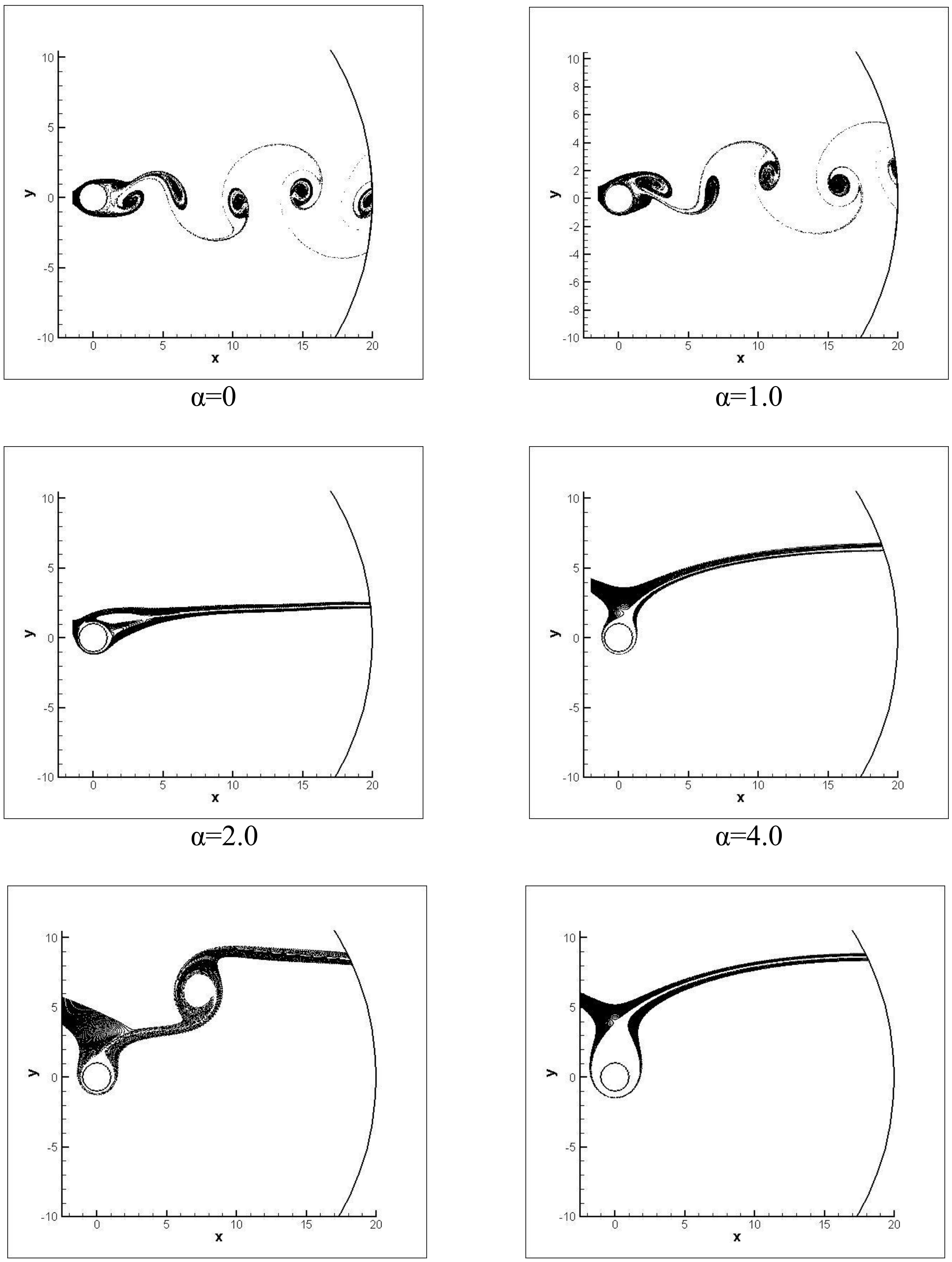


Figure 1. Lift coefficient history at Re=200 for different rotating speeds.

plots all had the same dimensionless frequency, which is about 10 dimensionless times, up to $\alpha = 2$. Note that, by $\alpha = 2$, the oscillations of C_L have been damped by the cylinder rotation and the frequency of the oscillation (at $\alpha = 2$) had decreased slightly before the damping occurred. The C_L oscillation returns in the range $4 < \alpha < 5$. Figure 1 shows the C_L behavior at a value of $\alpha = 4.5$ and then the oscillation vanishes again by $\alpha = 5$. The oscillatory period for $\alpha = 4.5$ is significantly larger, at about 60 dimensionless times, than during the oscillations which occurred at the lower values of α. The magnitude of the oscillation is also significantly greater. The C_L peak-to-peak range at the lower values of α is about 1.2 while the peak-to–peak range at α = 4.5 is about 3. This suggests that a different kind of mechanism is exciting the flow at this higher value of α. To determine what that mechanism is, we performed streak-line calculations for the entire range of α values. Selected results are shown in Fig. 2.



α=0 α=1.0

α=2.0 α=4.0

α=4.5 α=5.0

Figure2. Streaklines at Re=200 for different rotating speeds

These results show that conventional vortex shedding is suppressed for $\alpha \geq 2$. What has happened at α = 4.5 is that a vortex is formed from the shear layer from the flow off the top side of the rotating cylinder, i.e., the generated vortex has counter-clockwise rotation. This shear layer rolls into a circular vortex as it is convected downstream as shown in Fig. 2. This process repeats itself in a regular pattern. Mittal and Kumar (2003) also noticed this second onset of instability and plotted the vorticity field for it as well as for some of their other values of α.

Mittal and Kumar suggest that "a positive vortex is shed from the cylinder and the flow settles to a stable state". It seems that the streakline plots present a slightly different picture of this phenomenon. This "single vortex" seems to form downstream of the cylinder as the shear layer rolls up and becomes a vortical structure several diameters downstream. This is a different mechanism than the shear layer rollup immediately behind the cylinder. To demonstrate this second vortex formation, we have introduced a second set of streaklines to illustrate what has happened. This is shown in Fig. 3 at four different times in the formation cycle. The shear layer on the top of the cylinder is experiencing an instability that is growing with time. This instability rolls up into a vortex which grows as it moves downstream, eventually. This process repeats itself as time increases, forming a series of these large vortices. Compared to the C_L history in Fig. 1, we can see that, during this process, the extent of oscillation of C_L increases by a factor of three over that for the lower values of α (α<2) and the period of this large vortex is much greater that for these lower values of α.

In Fig. 4, we have presented a polar plot of C_D vs. C_L. for the values of α that we have considered at Re = 200. Notice that, at the lower values of α at Re=200, the polar plot shows a variation in C_D of up to +/- 0.25 about a mean value unique to each value of α for α < 3. For $3 \leq \alpha \leq 4$, the polar plot collapses to constant values of C_D and C_L. Notice that C_D is now negative for C_D At α = 4.5, the polar plot reflects that

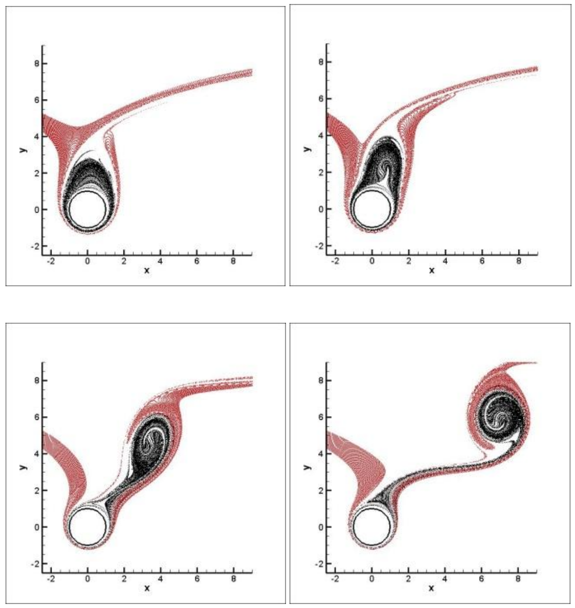


Figure 3. Streaklines of Re=200 at α = 4.5 for dimensionless time t =114 (a), 121 (b), 129 (c) and 134 (d).

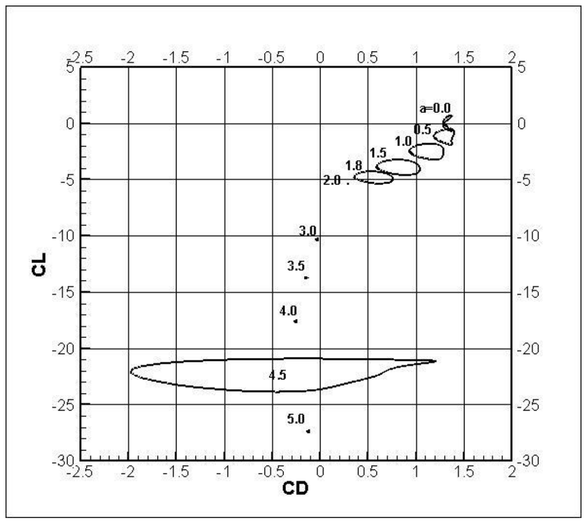
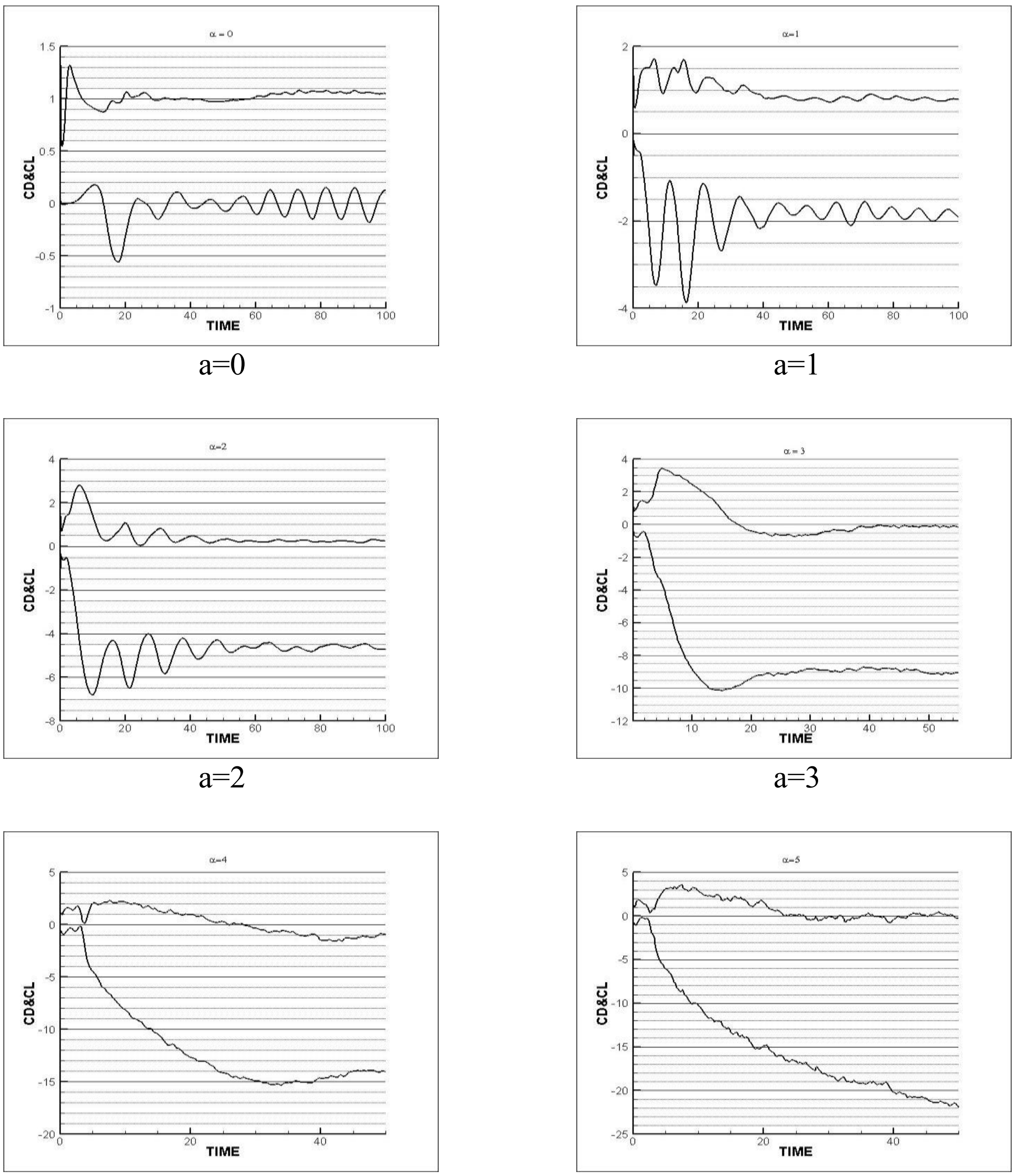


Figure 4. Polar plot of C_D and C_L at Re=200

large vortex behavior shown in Fig. 2. The drag coefficient ranges in value from -2 to +1.2. The lift coefficient ranges from about -21 to about -24 during this single-vortex formation event. At α = 5, the drag/lift polar plot again reduces to a point, with the inference that the there is no time-dependence in the drag and lift values at α=5.

We have also performed calculations at Re = 1000 for several values of α: 0, 1, 2, 3, 4, and 5. These lift and drag coefficient plots, shown in Figure 5, are not nearly as regular as seen in the C_L plots at Re = 200 because the wake flow is now being recognized as turbulent. This irregularity



a=0 a=1 a=2 a=3 a=4 a=5

Figure 5. Lift coefficient history at Re=1,000 for different rotating speeds

with an increase in Re is a fairly common result in a CFD calculation. At $\alpha = 0$, which is a uniform flow past a nonrotating cylinder, the drag and lift coefficients have their expected steady flow values for flow past a fixed cylinder with a turbulent wake. For $\alpha = 1$, the lift and drag results appear to be similar as at $\alpha = 0$, but the mean C_L value has dropped from zero at $\alpha = 0$ to about -1.8 with some damping indicated due to the steady decrease in the oscillations of the C_L plot. For $\alpha = 2$, the C_L oscillations are damped further with the mean value being at about -4.6. For $\alpha = 3$, both lift and drag have essentially lost their time-dependent behavior. The mean C_D value is now negative, about -0.5, and the mean C_L value is about – 8.5.

At $\alpha = 4$, the mean C_D value is about zero and the lift coefficient has a mean value of about -15 and, at $\alpha = 5$, the mean C_D value is about 0.1 while the mean C_L value is at about -19.

A comparison of C_L values for like values of α at the two different Reynolds numbers is meaningful. At Re=200 and 1000, the C_L values for $\alpha = 1$ are -2.5 and -1.8 respectively; at $\alpha = 2$, the C_L values are -5.5 and -4.6; at $\alpha = 3$, the C_L values are -10.2 and -8.8; at $\alpha = 4$, the C_L values are -17.7 and -15.2; and at $\alpha = 5$, the C_L values are -27.4 and -19. These values show that increasing the Reynolds number decreases the lift coefficients for like values of α. In addition, the difference in lift coefficients is increasing with increasing α. These trends require closer examination which will be finished shortly.

5. Conclusions

This has been a computational study to see what affect that increasing the Reynolds number has on the lift and drag for the range of values of α considered in this study. It was determined that increasing the value of α at a given Reynolds number caused the drag to decrease slightly and the lift to decrease significantly, i.e., to become more negative. It was also found that the difference in lift coefficients decreased from Re =200 to Re= 1000 with increasing values of α, with the difference increasing as α increased. In addition, an unusual vortex formation occurred at $\alpha = 4.5$ for Re = 200. The mechanism for this formation is still under investigation. We will also explore the possible occurrence of a similar phenomenon at Re =1000. This is a study which has the potential for significant practical application and our expectations are to carry the Reynolds numbers to much higher values to gain a better understanding of this flow.

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