

Suppression of the unsteady vortex wakes of a circular cylinder
pair by a doublet-like counter-rotation

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Suppression of the unsteady vortex wakes of a circular cylinder pair by a doublet-like counter-rotation

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The present investigation examines the suppression of unsteady, two-dimensional wake instabilities of a pair of identical circular cylinders, placed side-by-side normal to freestream at a low Reynolds number of 150. It is found that when the cylinders are counter-rotated, unsteady vortex wakes can be completely suppressed. At fast enough rotational speeds, a virtual elliptic body is produced by a closed streamline, strongly resembling a doublet potential flow.

Nomenclature

C_D	=	drag coefficient
C_L	=	lift coefficient
d	=	diameter of circular cylinder
dt	=	time step
g	=	gap (between two circular cylinders) to diameter ratio
Re_d	=	Reynolds number based on diameter
U	=	uniform freestream velocity
ω	=	rotational velocity magnitude of circular cylinder
Ω	=	rotational velocity magnitude of circular cylinder at $2 \cdot U/d$

I. Introduction

THE flow past a pair of identical circular cylinders had been used as a model by various investigators who were interested in the interaction of vortex wakes of multiple bluff bodies in freestream. The previous studies were mostly experimental. The present paper takes a numerical approach to compare some results with some known experimental work, and investigates the use of counter-rotation to suppress the wake instabilities of a cylinder pair.

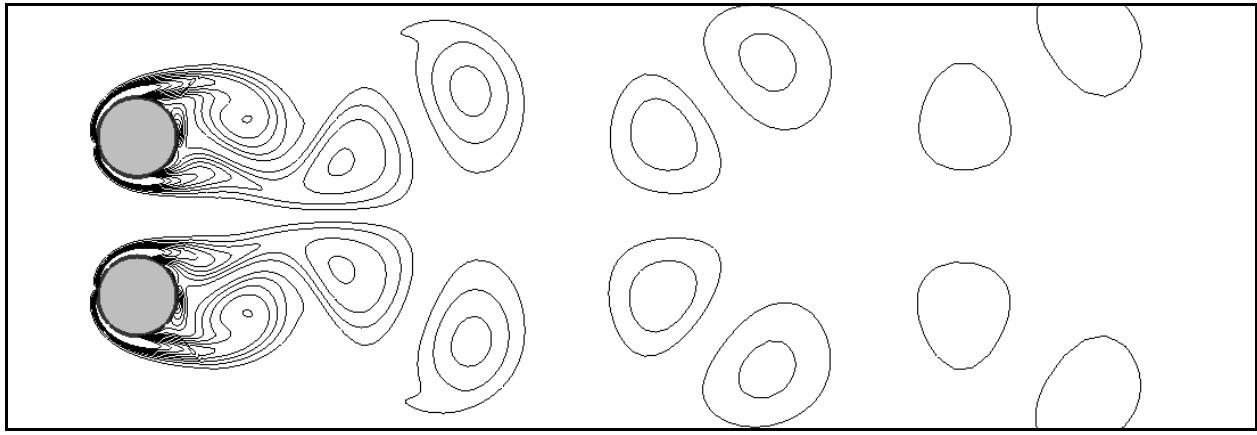
It is well known that when a circular cylinder is placed in a uniform freestream an unsteady separation develops, leading to a well-known von Kármán vortex street. In the low Reynolds number range of less than 250, the vortex wakes are purely two-dimensional. When a pair of identical circular cylinders are placed side-by-side in a close proximity, wake interaction consequently bounds to occur. Following the work of Bearman & Wadcock [1] and

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Zdravkovich [4], Williamson [2] classified the vortex street of the cylinder pair into two categories—*anti-phase* and *in-phase*—for gap-to-diameter ratios in the range of $1.0 < g < 5.0$.

As noted by Williamson, the anti-phase mode is predominant and stable since each vortex lobe generally keeps its form until being gradually dissipated downstream of the bodies (Figure 1). The numerical results in this report are obtained numerically by the use of a commercial code, CFD-ACE+ by ESI Corporation. The CFD model used in this study contains somewhere between 150,000 and 200,000 computational cells depending on the physical geometry such as g , which dictates the way meshes are formed around the cylinders. The meshing pattern radiates from each cylinder in a geometric-progressive manner. The grid spacing next to the cylinder wall surface is approximately $0.004 \cdot d$. There are 280 grids circumferentially surrounding each cylinder surface.



**Figure 1: Iso-contour plot of vorticity of an *anti-phase* vortex street past a circular cylinder pair,
 $Re_d = 150, g = 1$.**

Figure 2 illustrates the in-phase vortex shedding mode which Williamson experimentally observed as being unstable since each vortex lobe does not keep its form downstream of the bodies. Each “binary” vortex—a pair of like-sign vortices—tends to coalesce into a larger single vortex cell before eventually being dissipated far downstream. To obtain a numerical result for an in-phase mode, we found that one can use the technique of perturbing the flow velocity by artificially injecting a non-streamwise component into the computational domain for a few time steps before removing it. The purpose is to “trip” the flow so that the non-streamwise component will encourage the flow to develop into an in-phase pattern. Another method which was used successfully is to artificially increase dt and/or limit the convergence criteria so that the residual error builds up for a few time steps. When dt is throttled back down and reasonable convergence criteria is re-established (typically at least four order of

improvement is sought in our computation), the error residual in the computational domain tends to encourage the in-phase instability to form.

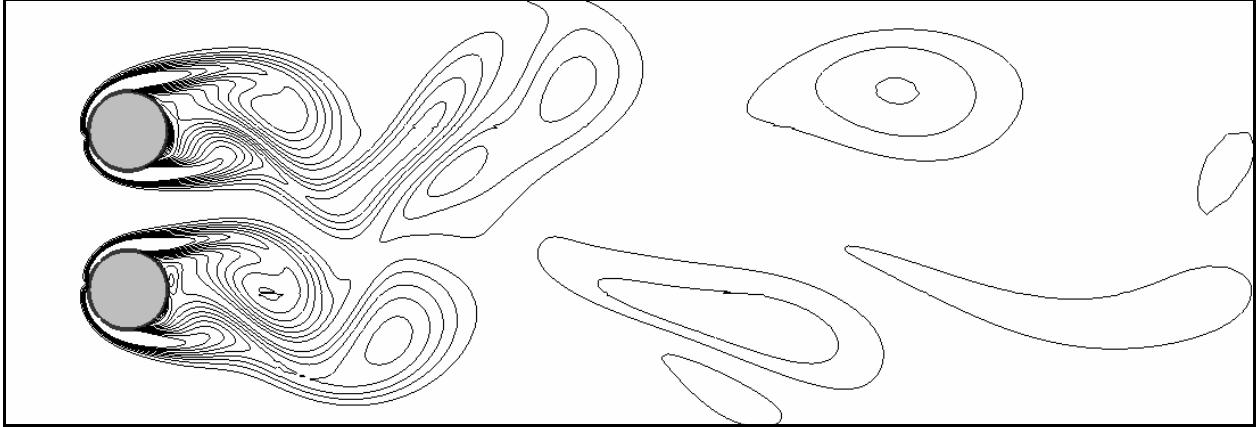


Figure 2: Iso-contour plot of vorticity of an *in-phase* vortex street past a circular cylinder pair,
 $Re_d = 150, g = 1$.

II. Configurations of a counter-rotating circular cylinder pair

IN a uniform flow past a pair of identical circular cylinders for the Reynolds number range of approximately 50 and above, it is inevitable that flow instabilities would incur in the immediate wakes downstream of the cylinders. The vortex wakes can be three-dimensional and complex or simply two-dimensional depending on the Reynolds number of the flow. If two identical circular cylinders are rotated at the same speed but in the opposite direction, it is hypothetically conceivable that a flow pattern similar to a doublet in the potential flow theory can be produced. We focus our analysis on the control of two-dimensional vortex wakes. More specifically, we choose $Re_d = 150$ and $g = 1$ as a basis of flow for our current numerical experiments. There are two possible configurations:

- 1) A doublet-like direction (Figure 3)—top cylinder rotates clockwise and bottom counter-clockwise at the same speed, ω .
- 2) A reverse-doublet-like direction (Figure 4)—top cylinder rotates counter-clockwise and bottom clockwise at the same speed, ω .

We also define the magnitude of the cylinder rotation as $\Omega = 2 \cdot U/d$. So if we rotate each cylinder at a speed of $\omega = 1\Omega$, it means that the surface velocity magnitude of the cylinder is exactly equal to the uniform velocity

magnitude. Each cylinder in any pair configuration will be spun at various equal and opposite velocities to determine the effect on and the behavior of the vortex wakes.

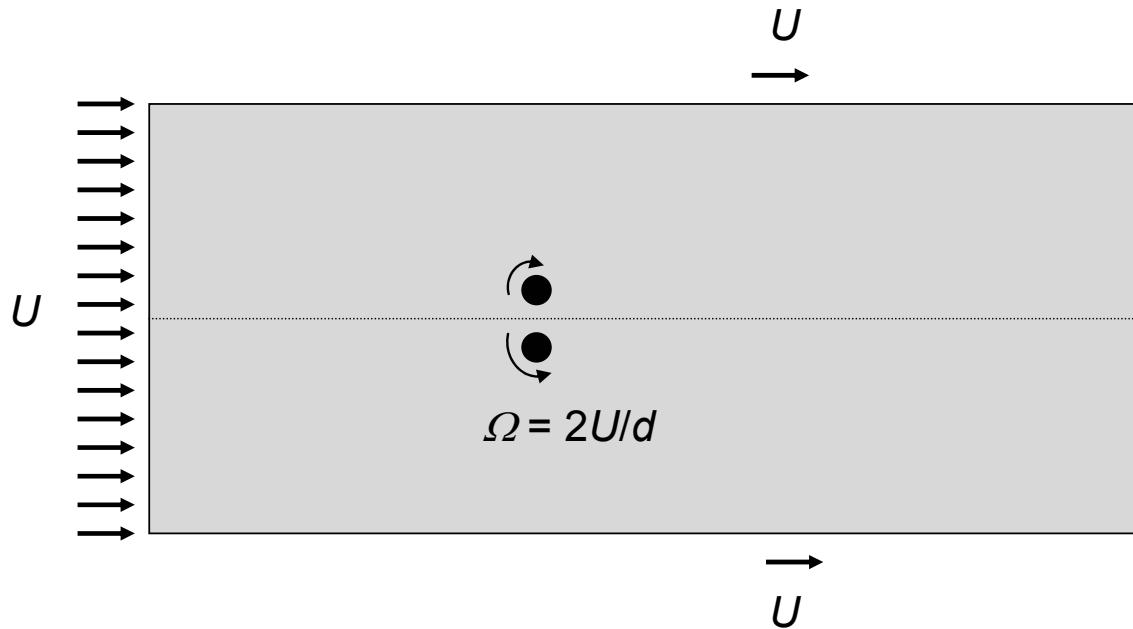


Figure 3: A doublet-like configuration

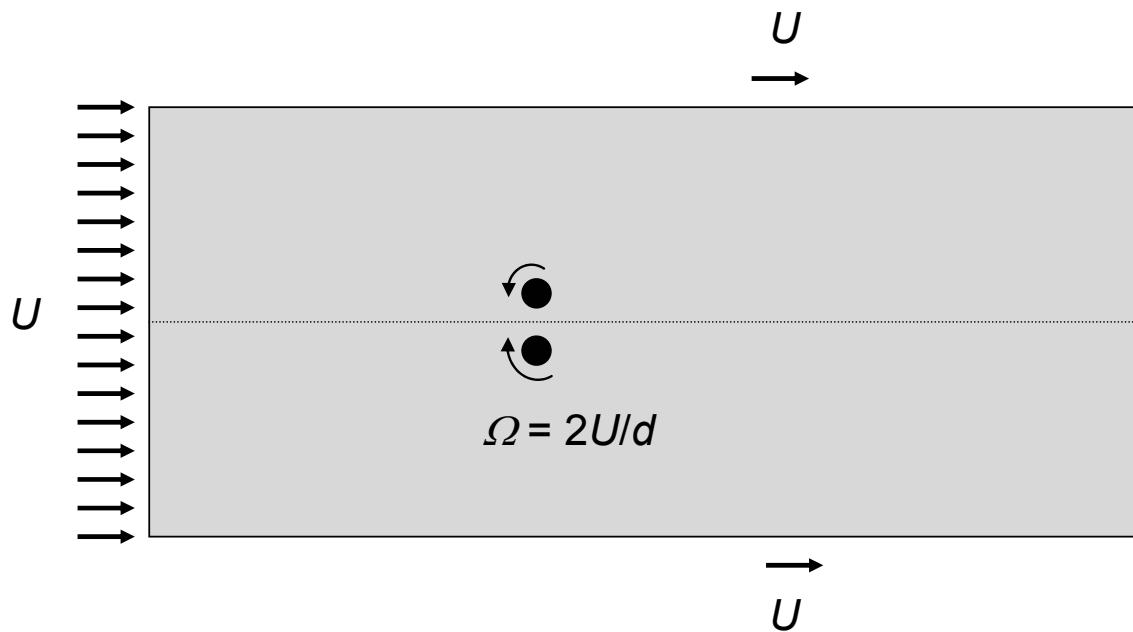


Figure 4: A reverse-doublet-like configuration

III. Numerical results of a doublet-like rotating circular cylinder pair

ILLUSTRATED in Figure 5 is the instantaneous vorticity plot of counter rotating circular cylinders in a doublet-like rotational setting as compared to an in-phase shedding of a non-rotating pair of cylinders. We used the results obtained from the in-phase shedding case of the non-rotating cylinder to start the flow of the rotating case. In the case of $g = 1$ at $Re_d = 150$, it is apparent that the rotation of cylinders encourages the wakes to coalesce much sooner than the non-rotating case. The unsteady vortex wakes shed off each rotating cylinder also seem to be attenuated as the magnitude of each vortex lobe appear weaker. The attenuation of the fluctuating lift and drag can be seen on Figure 6. The rotation has the effect of pushing of cylinders apart as apparent from the spread of the lift coefficients between top and bottom. The rotation also helps streamline the flow past the two cylinder bodies whereby a reduction in overall drag coefficients is observed. Note that the rotation also reduces the sum of the forces on both cylinders. The characteristics of vortex wakes as well as the reduction in flow-induced forces on the bodies generally seem to be in a reasonable agreement with the recently reported results of Yoon *et al* [3].

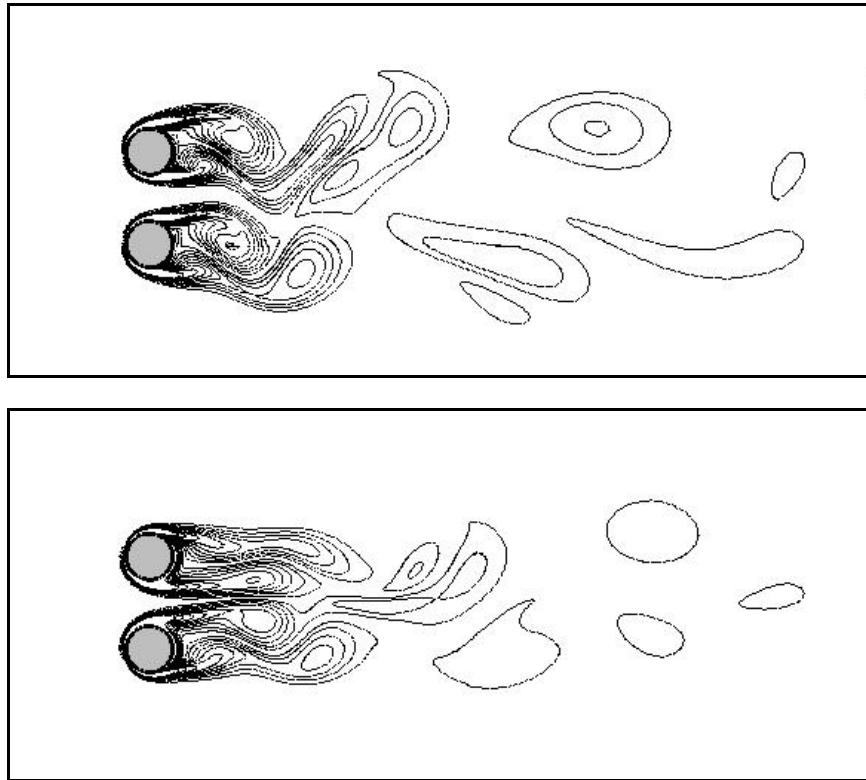


Figure 5: Vorticity plots of flow past a non-rotating pair of circular cylinders (top)

and past a doublet-like pair of circular cylinders counter-rotating at $\omega = 1\Omega$ (bottom), $Re_d = 150$, $g = 1$

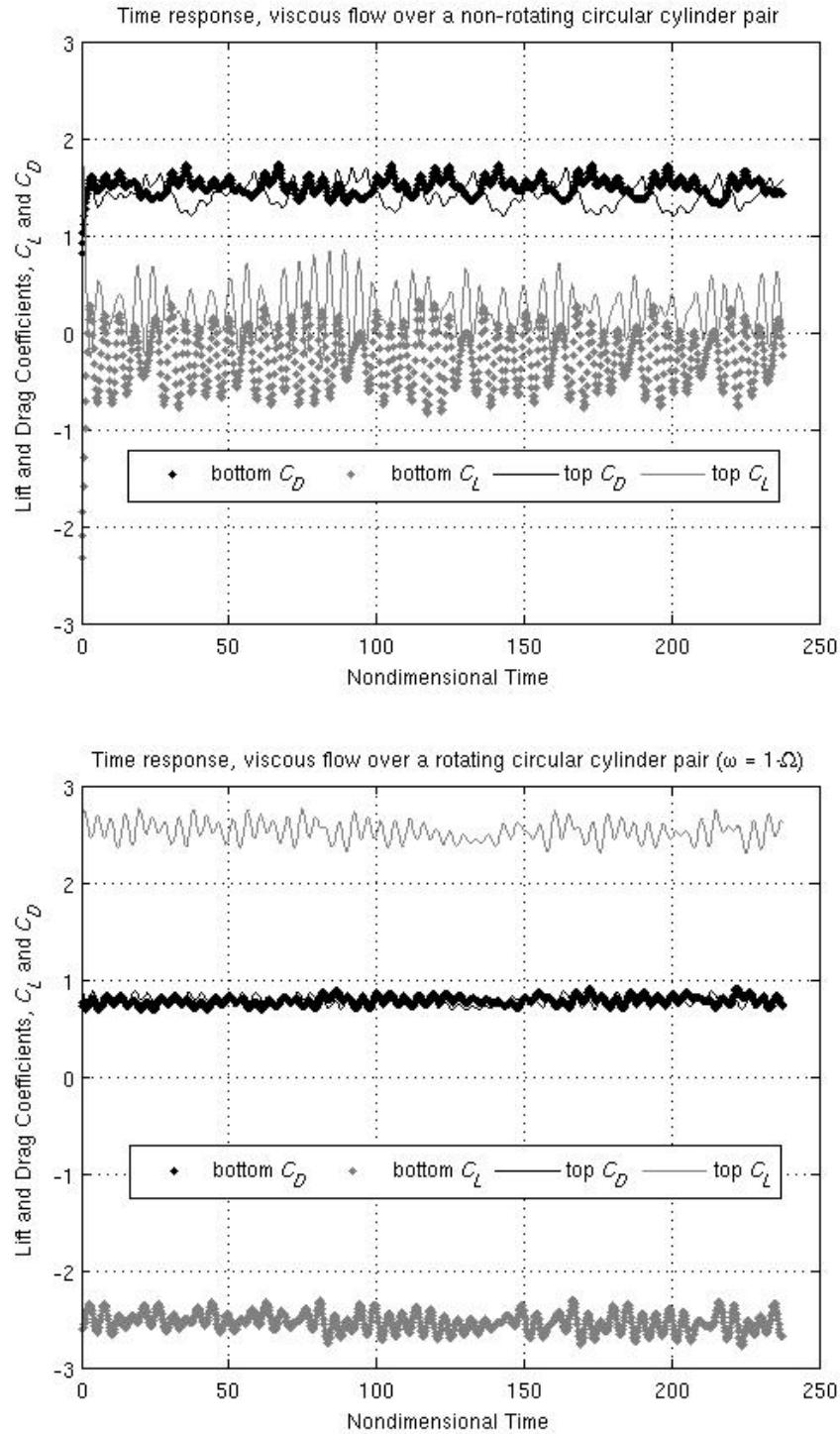


Figure 6: Time response of lift and drag coefficients of each circular cylinder: Non-rotating pair of circular cylinders (top) and doublet-like pair of circular cylinders counter-rotating at $\omega = 1\Omega$ (bottom),

$$Re_d = 150, g = 1$$

Symmetrical steady shedding

When the rotational speed is increased further the vortex wakes can be completely suppressed as seen on Figure 7, which plots the streamlines to illustrate the evolution of steady wakes as a function of rotational speed. It appears that the flow past a circular cylinder pair stops shedding unsteady vortex wakes at a rotational speed between 1Ω to 1.5Ω . When a steady flow is produced by rotation, the entire force fluctuation on each cylinder is totally suppressed and, as a result, the total sum of the lift coefficient, C_L , of the cylinder pair is exactly zero. Somewhere between the rotational speed of 2.5Ω and 2.75Ω , a closed vortex system is formed similar to a potential doublet in a form of virtual elliptic body (Figure 10). Figure 8 shows the lift and drag coefficients of a doublet-like rotating circular cylinder pair when steady flow is reached. The total lift coefficient C_L is zero while the total drag coefficient C_D of the circular cylinder pair is significantly reduced as the rotational speed is increased. Because the flow is symmetric along the horizontal center line (half way between the two cylinders), C_D of the top cylinder must be precisely the same as the bottom cylinder. The form drag becomes negative when the rotational velocity is increased beyond 1.8Ω (Figure 9). Remarkably the total drag coefficient is slightly negative at a rotational speed of 2.5Ω , indicating that the work that is put into rotating the cylinder not only stabilizes the flow but can be converted into forward thrust. As the rotational speed is increased beyond 2.5Ω and a virtual elliptic body appears, the form drag starts to increase as the size of the virtual body increases. But the total drag remains small because the frictional contribution to the horizontal force starts to decrease at about the same rate. Both contributions change sign at a rotational speed around 4.3Ω , and eventually as the rotational speed is further increased net thrust is again observed.

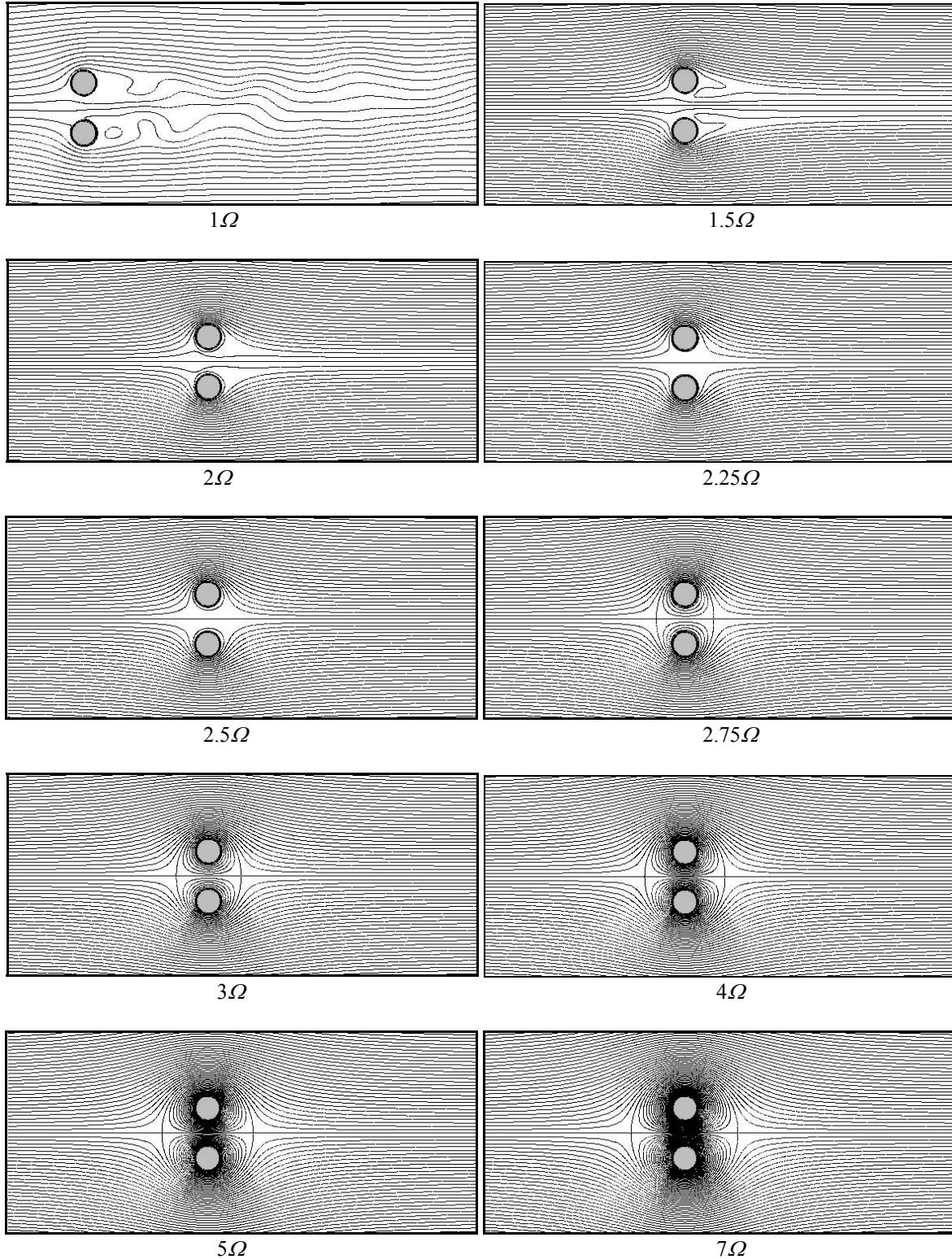


Figure 7: Streamlines showing the evolution of steady flow with increasing rotational speeds, $Re_d = 150, g = 1$
(Unsteady flow: 1Ω ; Steady flow: $1.5\Omega, 2\Omega, 2.25\Omega, 2.5\Omega, 2.75\Omega, 3\Omega, 4\Omega, 5\Omega$ & 7Ω)

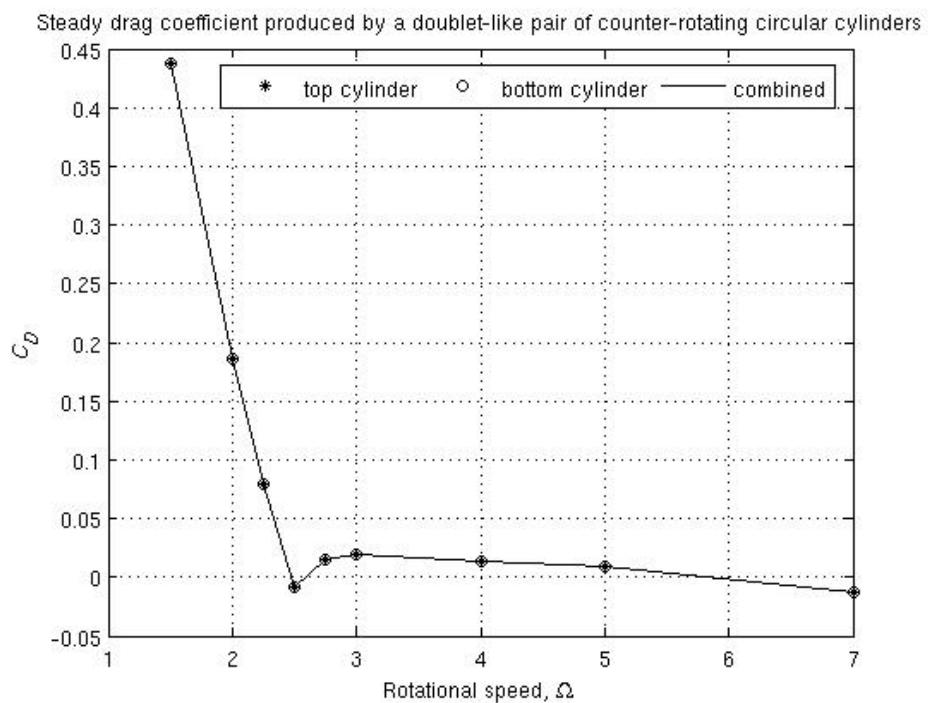
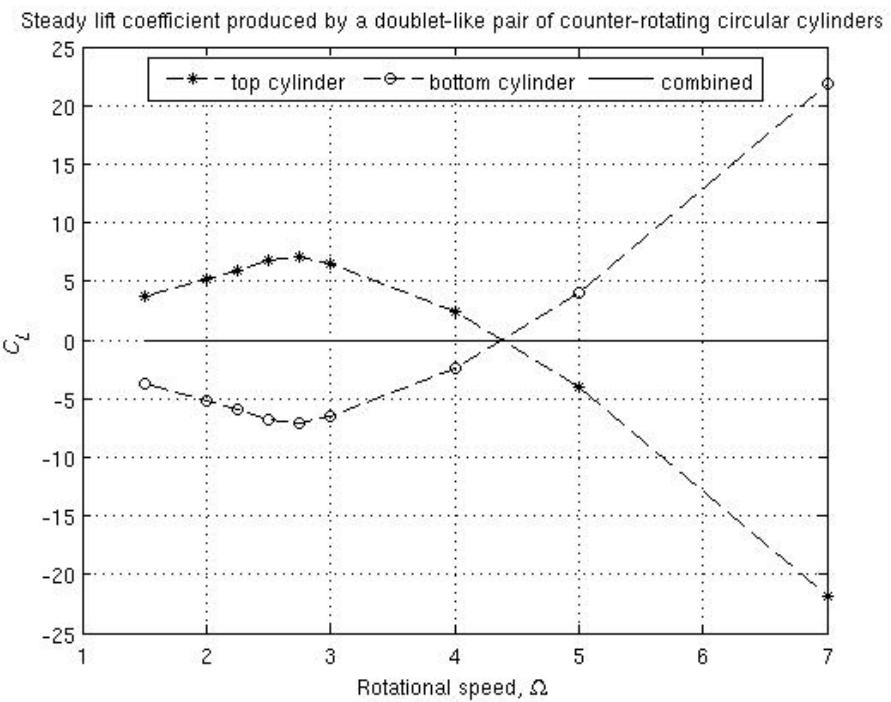


Figure 8: Lift and drag coefficients of a pair of counter-rotating circular cylinders (steady flow),

$$Re_d = 150, g = 1$$

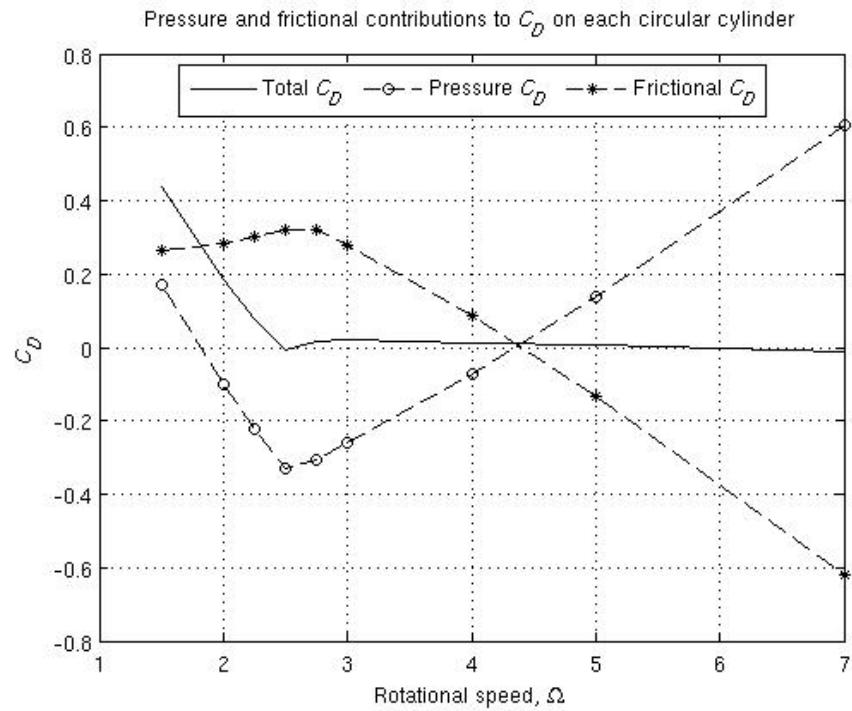


Figure 9: Pressure and frictional contributions to C_D on each circular cylinder (steady flow), $Re_d=150, g = 1$

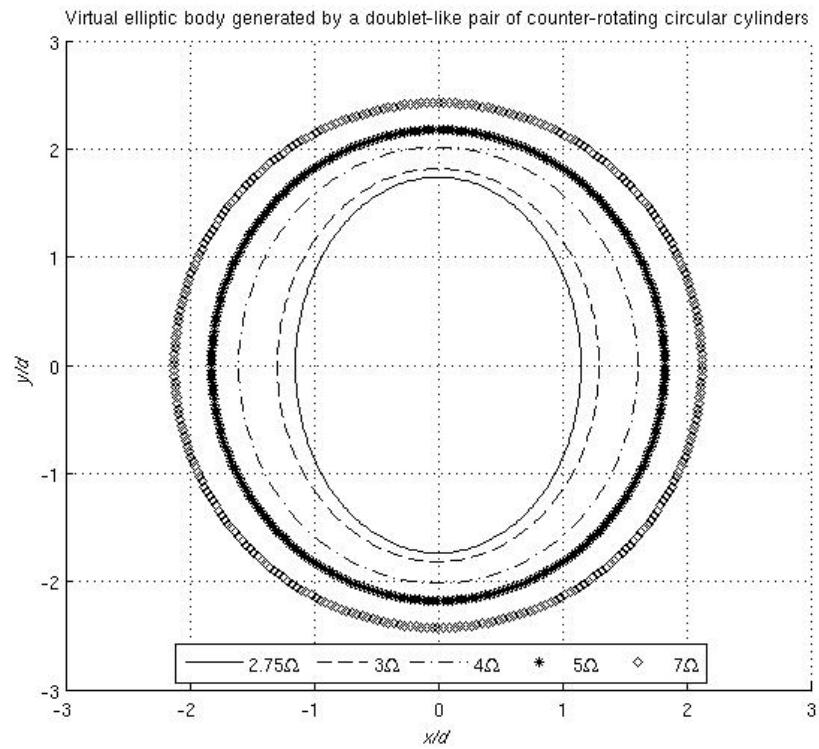


Figure 10: Virtual elliptic body (closed vortex system) at various rotational speeds, $Re_d=150, g = 1$

IV. Numerical results of a reverse-doublet-like rotating circular cylinder pair

BY analogy, it is a rational assumption that a steady flow solution can be produced even if the cylinders rotate in a reverse-doublet direction (Figure 4). In the reverse direction, vortex wakes from the top and bottom cylinders are forced apart such that the chance of each vortex street interfering with one another rapidly diminishes with increasing rotational speeds. This apparently lessens the ability to break down vortex wakes as compared to the more effective doublet-like rotation. From our limited study, we found that a steady flow can be achieved at an approximate rotational speed of 3.5Ω and upwards. We also noticed that C_D in general is substantially higher than when the cylinders are rotated in the other direction. Also in this range, the two cylinders are attracted by opposing vertical forces of equal magnitude which increases with speed.

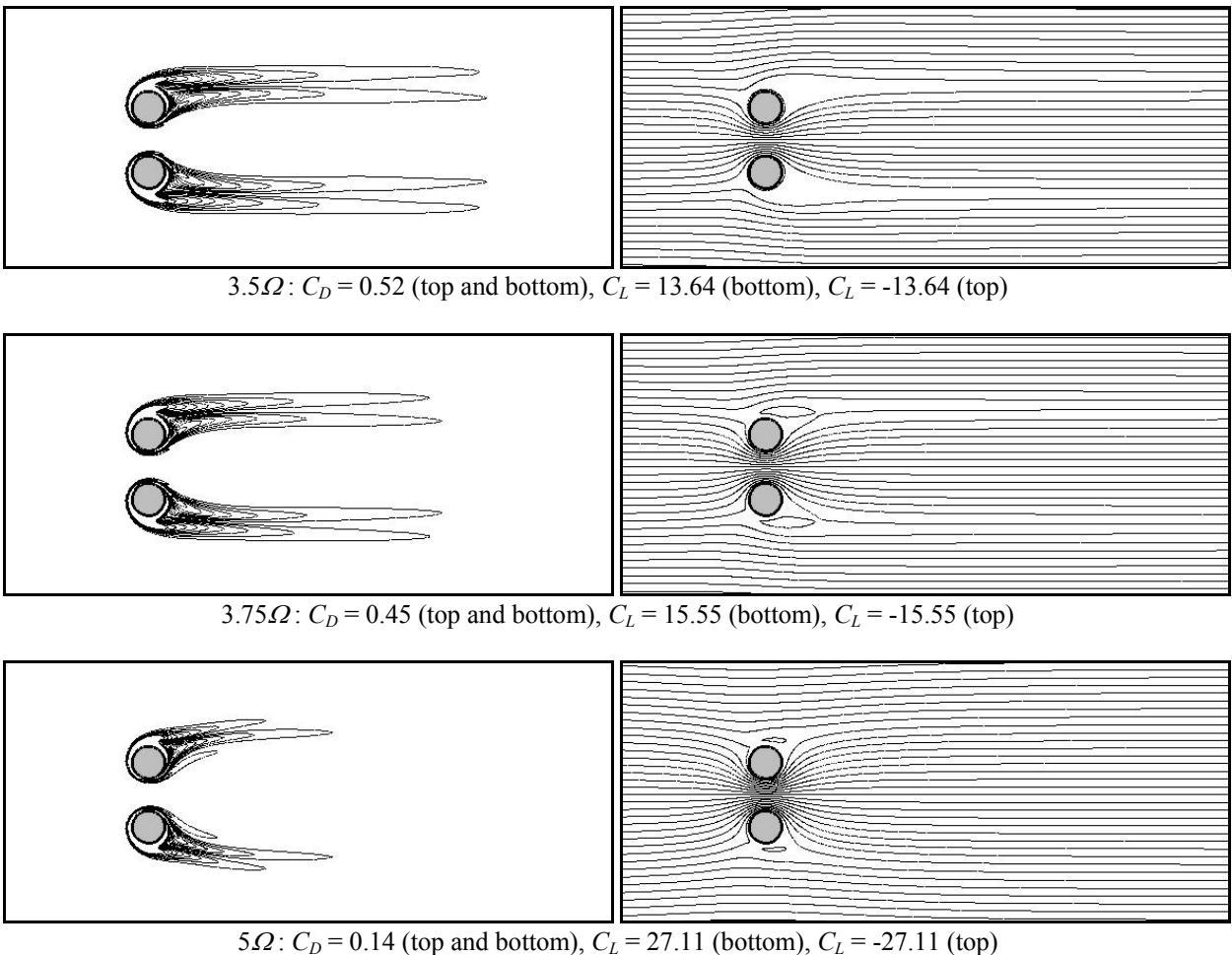


Figure 11: Flow patterns of a reverse-doublet-like circular cylinder pair counter-rotating at selected speeds:

Vorticity (left column), streamlines (right column), $Re_d=150$, $g = 1$

V. Conclusion

IN this report, we have demonstrated by numerical simulation that unsteady vortex wakes can be completely suppressed by counter-rotating a pair of cylinders. There are essentially two possible directions of counter rotation—a doublet-like direction and the reverse. We have found that when the cylinder pair is rotated in a doublet-like direction, a significant drag reduction can be achieved and at high enough speeds a virtual elliptic body is formed. In the speed range from where the steady flow first develops (1.5Ω) to where the virtual elliptic body is first observed (2.75Ω), the drag reduction is achieved mostly due to the decrease in form drag, which actually becomes negative in the range beyond 1.8Ω . At higher rotational speeds the form drag starts to increase again and becomes positive beyond 4.3Ω . However, the total drag remains low because the frictional contribution to the horizontal force exhibits the opposite trend. Net positive thrust is observed at rotational speed of 2.5Ω , and again at very high rotational speeds. Unsteady vortex wakes can also be completely suppressed by rotating the cylinder pair in the reverse-doublet-like direction, though it is not quite as effective as the other direction. It takes approximately 3.5Ω to achieve steadiness while the drag count on each cylinder remains high. It seems very desirable at this point to verify these phenomena by experimental tests.

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