## 1. Problem description

When an object is placed in a free stream, a recirculation region is formed behind that object. At low Reynolds numbers, the flow is steady. However, as the Reynolds number is increased beyond a critical value (which depends on the object's shape), vortices are shed alternately from the top and bottom shear layers of the object. These vortices are called Von Karman vortices. In this study, I simulated the vortex shedding from a complex object in two-dimensional flow. The object I chosen in this project was a rectangular cylinder of aspect ratio 2. The varying parameter was the **Reynolds number (Re=40, 100, 200)**.

## 2. Details of the code

Fluent 17.1 was used for the simulation. We choose pressure-based type, absolute velocity formulation, steady in time. The flow of interest is planar.

The geometric parameters of the rectangular cylinder were the size of 0.1m ×0.05m with a tilt angle of 45° (representative diameter d=0.1m). The domain of flow has a height of 1.0m (10d) and a length of 2.5m (25d), 0.5m (5d) before the object and rest after the object. Inflow velocity was 1.0m/s. The diagram of geometry is shown as figure 1. Top and bottom boundaries conditions were set to zero derivative. Right boundary condition (outflow) was also set to zero derivative. Since the problem is two-dimensional and Reynolds number is 40, 100, 200, we assumed the flow is laminar. Regarding the fluid we used in our calculations, we chose air which has density of 1kg/m$^3$, viscosity should be calculated according to Reynolds number. Regarding the solution methods, SIMPLE scheme was used for pressure-velocity coupling. As for spatial discretization, we selected least squares cell based gradient, standard pressure and second order upwind momentum. Initialization method was chosen to be hybrid and we computed from the inlet since this part of boundary is the upwind direction of flow. Time step size was set to 0.2s, and total number of time steps were 50. Number of iterations per each time step was set to 20.

## 3. Numerical Parameters

Since we have varying Reynolds numbers Re=40, 100, 200, height of inlet of 1m, and a constant flow velocity at inlet of 1m/s, based on equation (1) below, to achieve target Reynolds number, we need to adjust air density and dynamic viscosity.

$$Re = \frac{\rho v L}{\mu} \tag{1}$$

The parameters used under different conditions are listed in Table 1 blow.

Table 1. Numerical parameters for Reynolds number of 1000

| Reynolds number | Flow type | Side length $L$ (m) | Grid size (m) | density $\rho$ (kg/m$^3$) | Boundary velocity $v$ (m/s) | Dynamic viscosity $\mu$ (kg/(m$\cdot s$)) |
|---|---|---|---|---|---|---|
| 40<br>100<br>200 | Laminar | 1.0 | 0.01 × 0.01 | 1 | 1 | 0.00025<br>0.0001<br>0.00005 |

## 4. Computational times

Iterations and CPU time for each are listed in Table 2 blow.

Table 2. Computational times to complete

| Reynolds number | Total Iterations | CPU time (s) |
|---|---|---|
| 40<br>100<br>200 | 1000 | 203.25<br>211.95313<br>223.25 |

## 5. Observations of numerical behavior

Numerical solutions are calculated based on each Reynolds number. Higher Reynolds number usually gives more stochastic result. i.e. numerical solution with higher Reynolds number requires longer computation time and consequently more cost. Figure 1 shows the residual convergence process for the three Reynolds numbers. From table 2 and figure 1 we can see that for different Reynolds number, the convergence rate did not change much, but the CPU time did change, higher the Reynolds number, longer the CPU time.

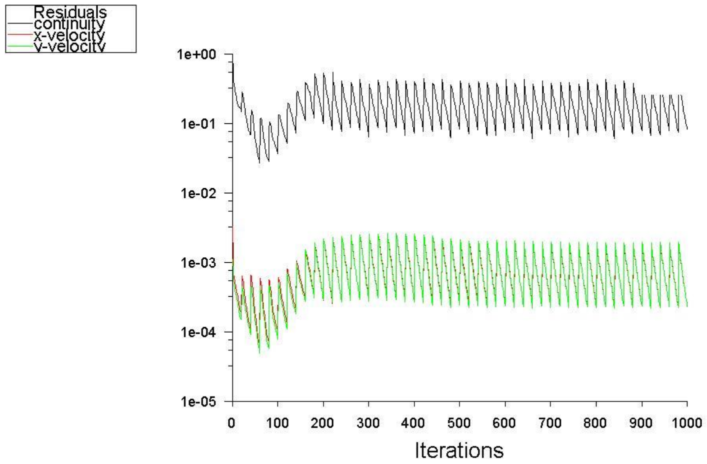



Figure 1(a). Convergence of mass and Momentum residuals (Re = 40)

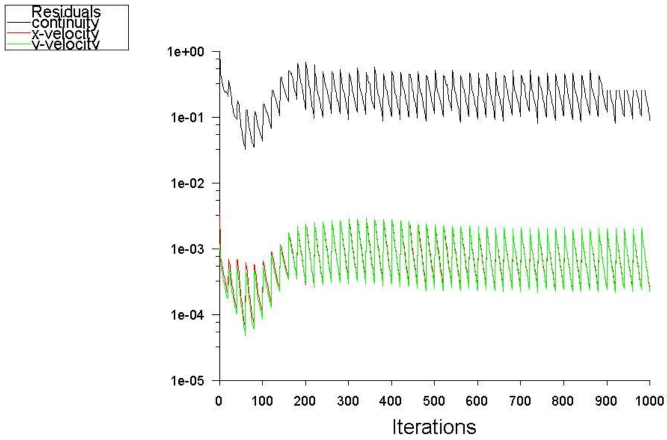



Figure 1(b). Convergence of mass and Momentum residuals (Re = 100)

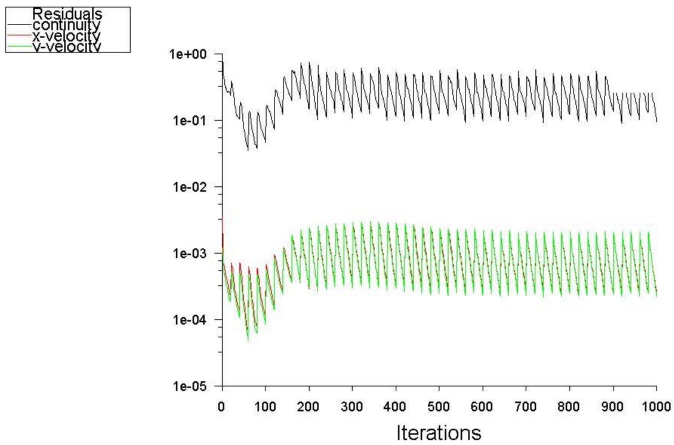


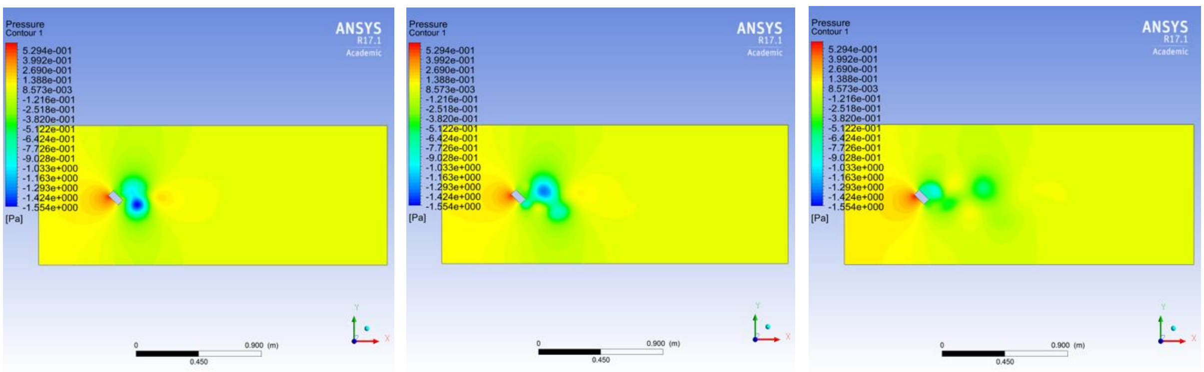

Figure 1(c). Convergence of mass and Momentum residuals (Re = 200)

## 6. Discussion of the flow physics

Contours of pressure for the three Reynolds numbers are shown in Figure 2.

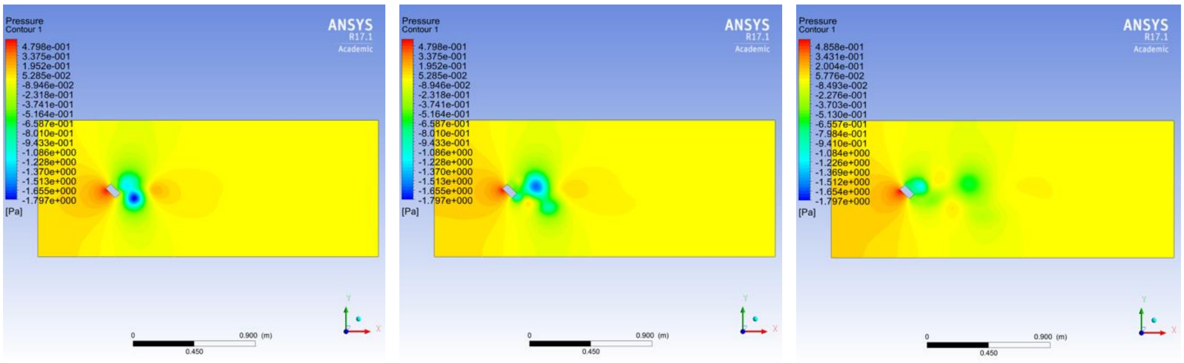
According to Figure 2,3,4, we observed that vortices are shed alternately from the top and bottom shear layers of the cylinder.

Line plots of velocity magnitude along line of x=0.5 for the three Reynolds numbers are shown in Figure 5. As we can see, for each Reynolds number, the centerline has the highest velocity magnitude compared to other locations. The velocity deceases in the direction of pointing away from the centerline. Also, for each line, the magnitude of velocity goes through a process that it decreases to zero first and then increases in inverse direction. This is mainly caused by the vortices in which the center velocity is zero while velocity away from the center gets higher. The velocities at edges are bounded by boundary conditions. Comparison between different grid sizes is plotted in Figure 4. Centerline velocity profile was used for both x and y directions. We can see that the magnitude gets bigger as the grid size increases. Contours of pressure for the three grid sizes are shown in Figure 5.



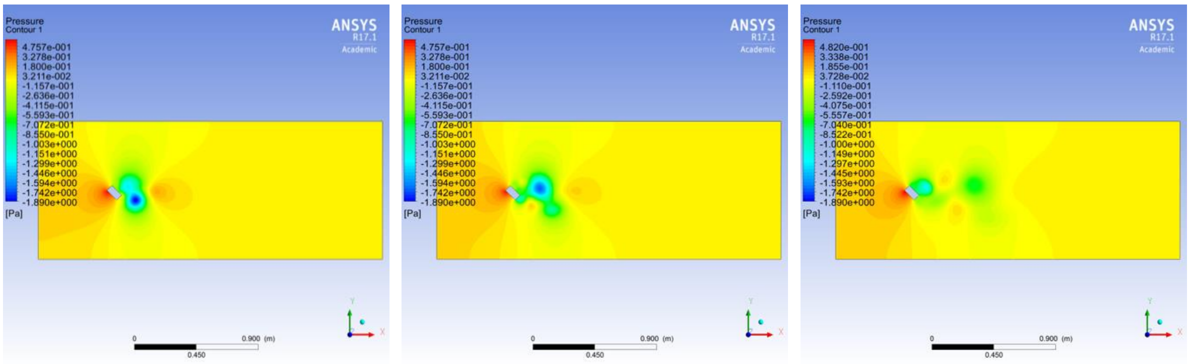

(a) t=1.0s (b) t=1.6s (c) t=2.0s

Figure 2(a)(b)(c). Contours of pressure (Re = 40)



(a) t=1.0s (b) t=1.6s (c) t=2.0s

Figure 3(a)(b)(c). Contours of pressure (Re = 100)



(a) t=1.0s (b) t=1.6s (c) t=2.0s

Figure 4(a)(b)(c). Contours of pressure (Re = 200)

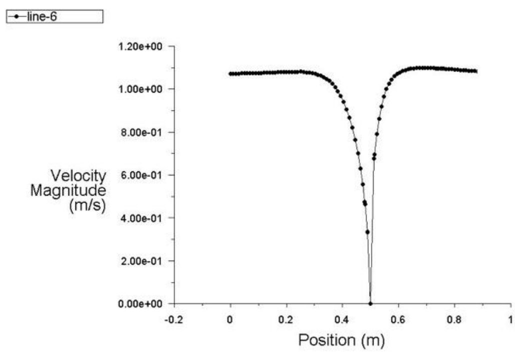



Figure 5(a). vertical velocity distribution at x = 0.5 (Re = 40)

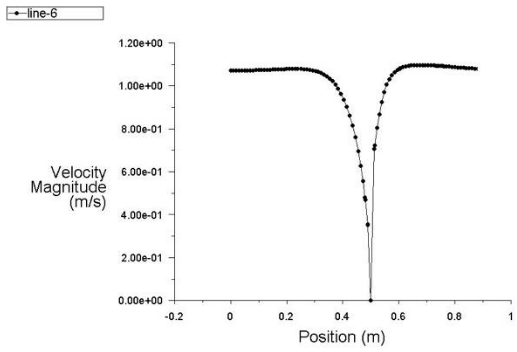



Figure 5(b). vertical velocity distribution at x = 0.5 (Re = 100)

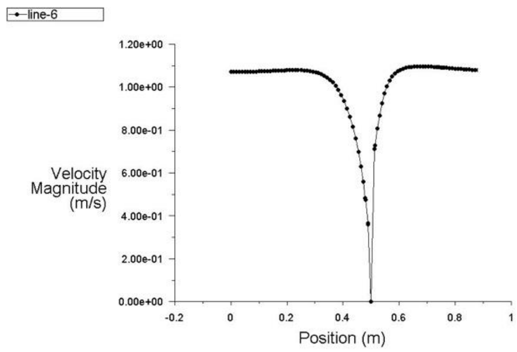



Figure 5(c). vertical velocity distribution at x = 0.5 (Re = 200)

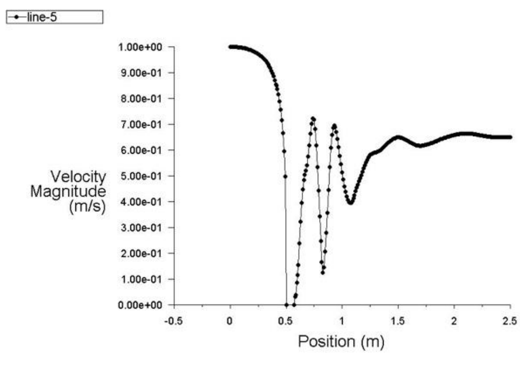



Figure 6(a). axial velocity distribution at y = 0.5 (Re = 40)

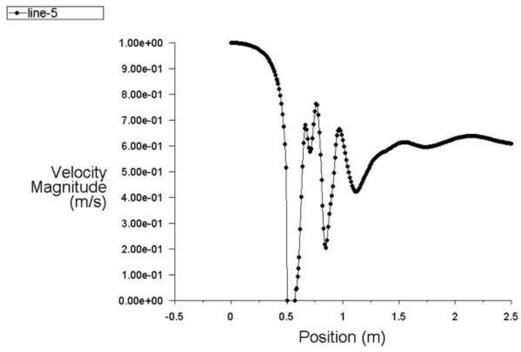



Figure 6(b). axial velocity distribution at y = 0.5 (Re = 100)

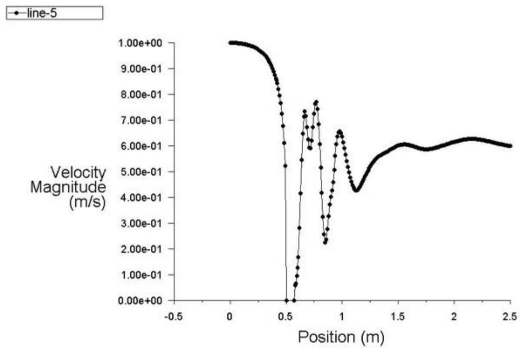



Figure 6(c). axial velocity distribution at y = 0.5 (Re = 200)

From Figure 7, we can see that although the drag coefficient was fluctuating, the average drag coefficient after about 3s of flow time increased when the Reynolds was being higher. The lift coefficient was keeping fluctuate for each Reynolds number, however, as the Reynolds number became higher and higher, the magnitude of fluctuating of lift coefficient become larger and larger.

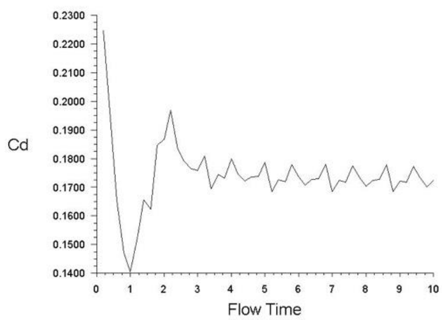



Figure 7(a). Drag coefficients residuals (Re = 40)

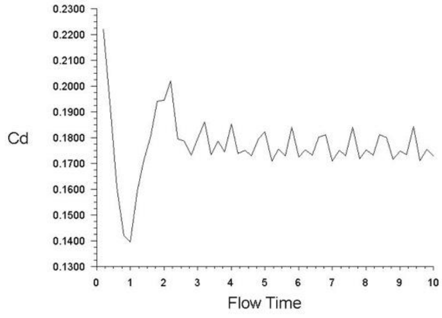



Figure 7(b). Drag coefficients residuals (Re = 100)

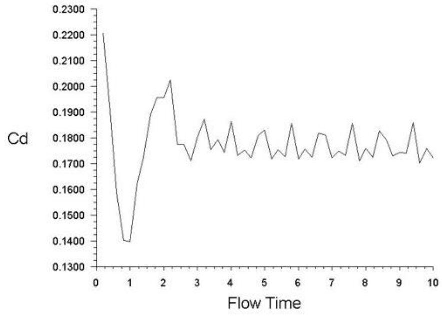



Figure 7(c). Drag coefficients residuals (Re = 200)

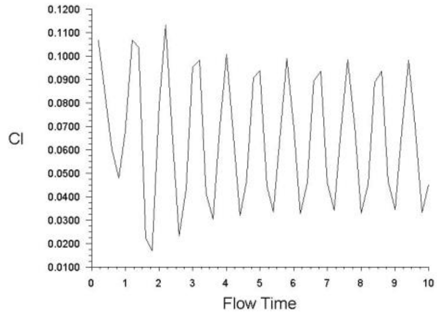



Figure 8(a). Lift coefficients residuals (Re = 40)

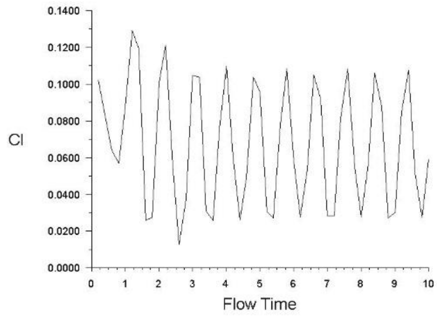



Figure 8(b). Lift coefficients residuals (Re = 100)

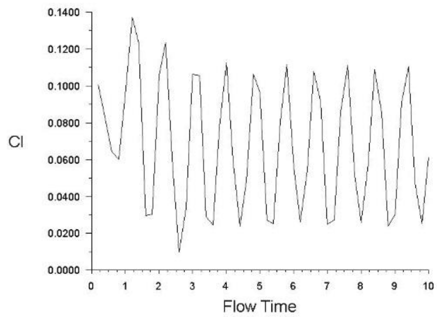



Figure 8(c). Lift coefficients residuals (Re = 200)