Report on

Laminar Flow across an Oscillating Cylinder

Case Study Project

Under the guidance of
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1. Introduction

Consider an incompressible, inviscid flow over a cylinder. Theoretical analysis shows that the flow wraps around the cylinder with the flow being symmetrical in both halves of the cylinder. It has two stagnation points, one in the front and the other behind the cylinder. Such a flow is shown in fig. 1. This kind of flow leads to the theoretical result that the pressure drag is zero. In reality, that isn't the case. This is called the d'Alembert's paradox.

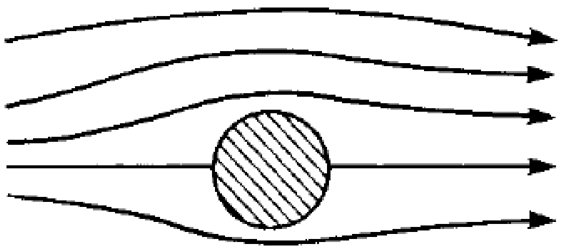


Figure 1. Ideal flow across a cylinder [1].

The real flow over a cylinder is quite different from that shown in fig. 1. This is mainly due to the influence of friction. A real flow over friction has a finite pressure drag. A flow of $Re = 140$ is shown in fig. 2. The alternately shed vortex pattern can be seen in the figure. They are called Karman vortex street, named after Theodor von Kármán.

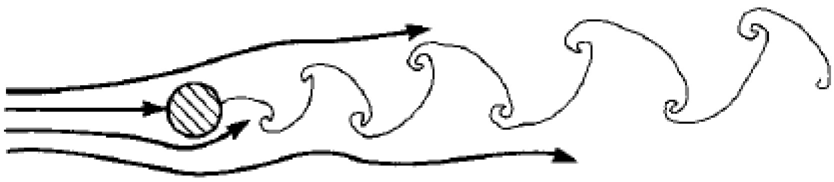


Figure 2. $Re = 140$ flow across a cylinder [1].

The phenomenon of vortex shedding can also be observed with the help of an oscillating cylinder in the cross-flow. Flow past a single oscillating cylinder is well researched [2]. These researches have greatly contributed to providing a better understanding of the flow characteristics governed by the amplitude and frequency of the oscillation.

2. Governing Equations

The Navier-Stokes equations for a viscous incompressible flow in an arbitrary domain is

$$\rho\left(\frac{\partial\vec{u}}{\partial t}+\nabla.(\vec{u}\vec{u})\right)=\nabla p+\nabla.\bar{\bar{R}}+\vec{S}_u$$

where all symbols have their usual meaning. $\bar{\bar{R}}$ is the stress tensor (symmetric) and $\vec{S}_u$ is the momentum source. The stress tensor is given by

$$\bar{\bar{R}}=\mu(\nabla\vec{u}+\nabla\vec{u}^T)$$

The Navier-Stokes equation is supplemented with the incompressibility condition

$$\nabla.\vec{u}=0$$

Given a fluid (ρ,μ), we have four equations and four unknowns ($\vec{u}$ and p).

3. Implementation in OpenFOAM

3.1. Problem Statement

The problem considers unsteady, incompressible, viscous flow over a cylinder of diameter 1 m oscillating at 0.2 Hz. The cross-flow is $Re=200$, hence laminar. The kinematic viscosity of the fluid is $\nu=0.01\ \mathrm{m}^2/s$.

3.2. Geometry & Meshing

The computational domain is shown in fig. 3. The domain is a rectangle of dimensions 22.5 X 10 m. The circular hole in the domain, of diameter 1 m, is the location of the cylinder.

Figure 3. The configuration of flow across an oscillating cylinder.

The meshing is done using OpenFOAM utility blockMesh. The geometry is divided into 20 blocks and each block has its own simpleGrading mesh. The mesh is inflated along x and/or y direction. Simple two dimensional O-grids are created around the cylinder. These O-grids are joined by a series of blocks to make the rectangular domain. The mesh is relatively fine near, around the cylinder.

Only one cell is considered alone the z direction making the simulation 2D in xy-plane.

Since the cylinder is oscillating, the domain is transient. Hence, moving meshes are used. This is done using dynamic meshing. When a solver uses dynamic meshing, it needs an additional solver to solve for the new grid at each time step. The corresponding solver used in this case is the displacementLaplacian solver. The mesh configuration at two different times are shown in figure 4 and 5.

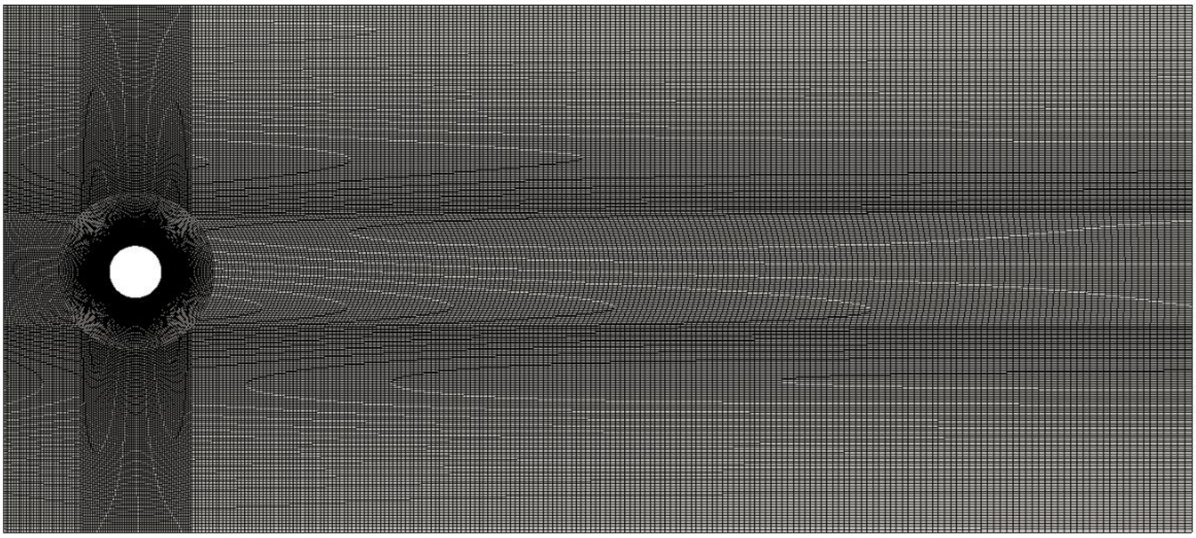


Figure 4. Mesh configuration at $T = 0$ seconds.

Fig. 4 shows the mesh configuration at the start of the simulation. The movement of the mesh can be observed in the fig. 5.

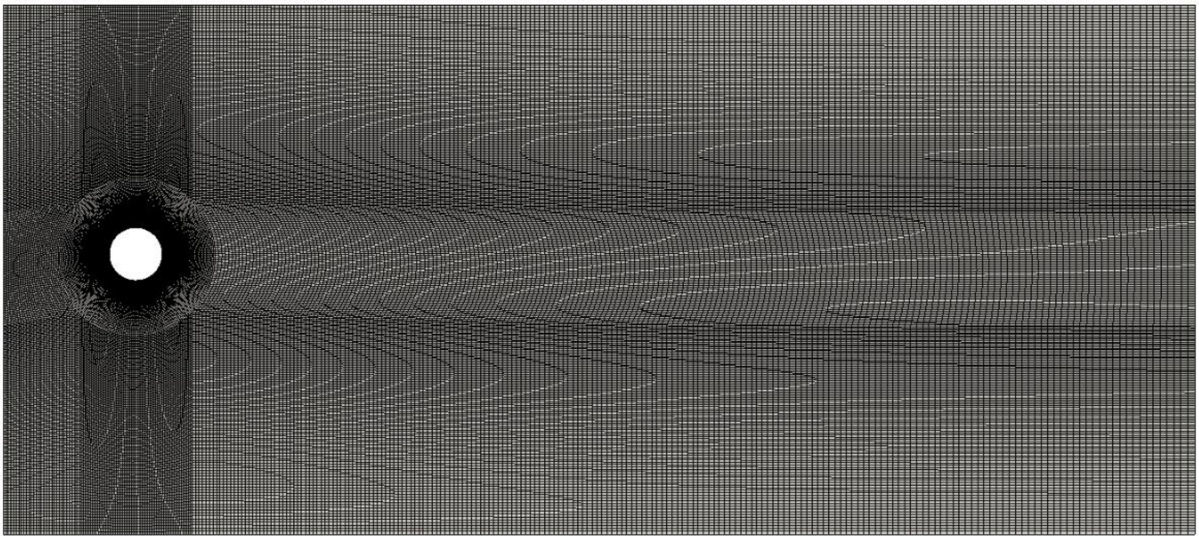


Figure 5. Mesh configuration at $T = 1.5$ seconds.

3.3. Initial & Boundary Conditions

The boundary conditions for various faces are described below:

a) Inlet: The left face of the domain

Pressure (p)	Zero Gradient
Velocity vector ($\vec{u}$)	$(2, 0, 0)$ m/s

b) Outlet: The right face of the domain

Pressure (p)	Zero Gradient
Velocity vector ($\vec{u}$)	Zero Gradient

c) Bottom and Top: The base and upper face of the geometry

Pressure (p)	Zero Gradient
Velocity vector ($\vec{u}$)	Slip

d) Cylinder: The surface of the cylinder

Pressure (p)	Zero Gradient
Velocity vector ($\vec{u}$)	No Slip; $(0, 0, 0)$ m/s

In addition to pressure and velocity, condition for point displacement of grid points are also needed. The boundary value at all faces except the cylinder is fixed at $(0, 0, 0)$ m.

The conditions for point displacement on cylinder is given below.

```
cylinder
{
    type            oscillatingDisplacement;
    omega           1.256;
    amplitude       (0 0.5 0);
    value           uniform (0 0 0);
}
```

The above data is for a body oscillating at 0.2 Hz and an amplitude of 0.5 m in the y-direction.

Uniform inlet condition of velocity is used as initial condition for simulation. A uniform pressure field of 0 Pa is the initial condition.

3.4. Solver

The laminar flow over an oscillating cylinder governing equations, as described in section 2, are solved using pimpleDyMFoam. The dynamic mesh is solved using the solver displacementLaplacian. The inverseDistance model is used for setting the mesh diffusivity. The dynamicMeshDict file looks as below

```
dynamicFvMesh   dynamicMotionSolverFvMesh;

motionSolverLibs ( "libfvMotionSolvers.so" );

solver          displacementLaplacian;


displacementLaplacianCoeffs
{
    diffusivity  inverseDistance 1(cylinder);
}
```

4. Results

The simulations are run on OpenFOAM 5.0 and the post processing is done using ParaView.

The velocity magnitude contour and streamlines at $T = 5$ seconds is shown in fig. 6 and 7 respectively.

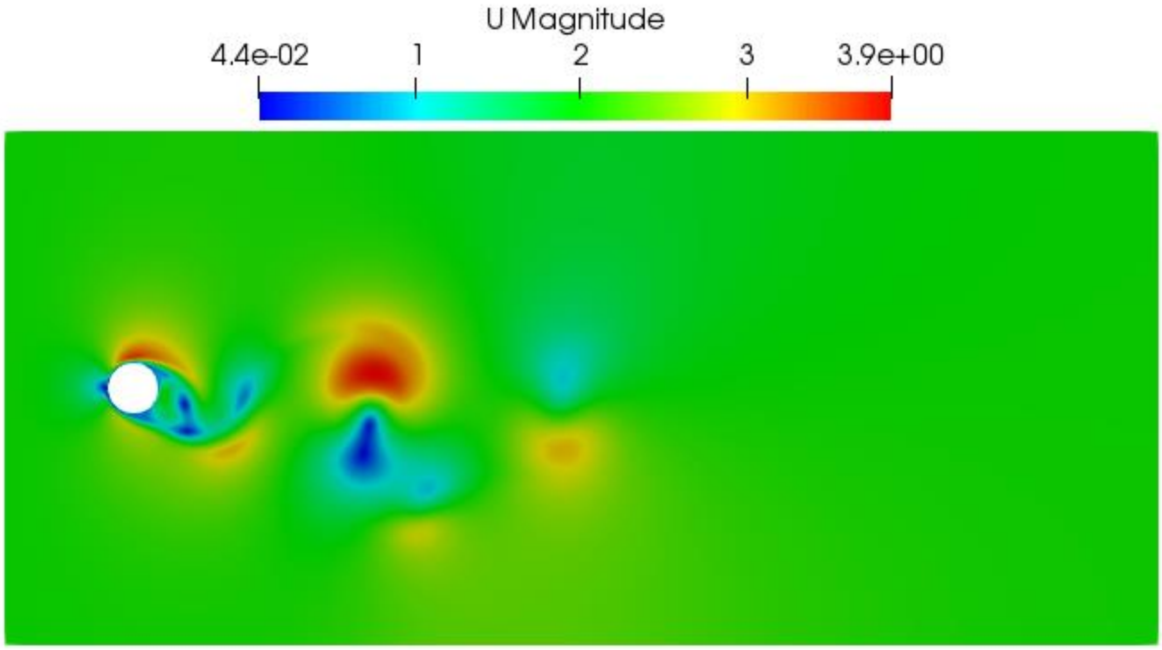


Figure 6. Velocity magnitude contour at $T = 5$ seconds.

The streamlines (fig. 7) clearly indicate the vortices induced in the wake of the cylinder.

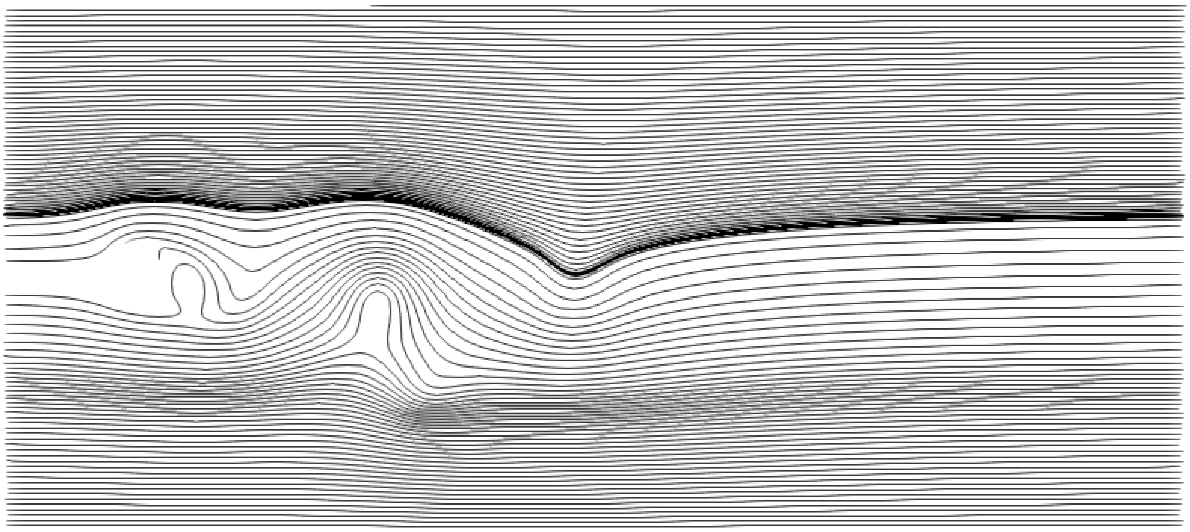


Figure 7. Streamlines at $T = 5$ seconds.

The streamlines at $T = 8.1$ seconds, as shown in fig. 8, clearly show the onset of a vortex generated at the wake of the cylinder.

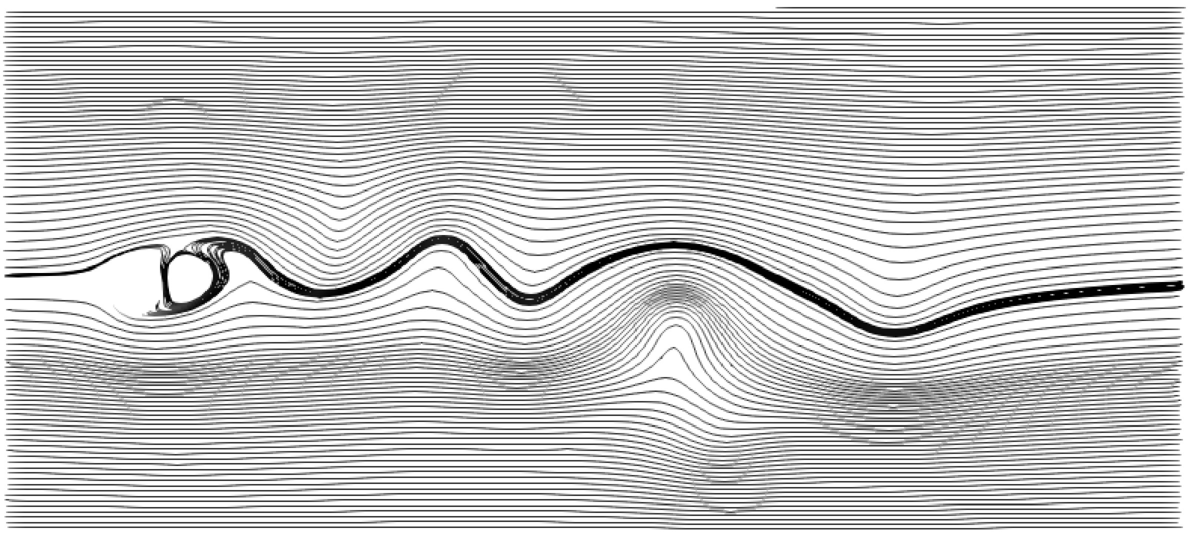
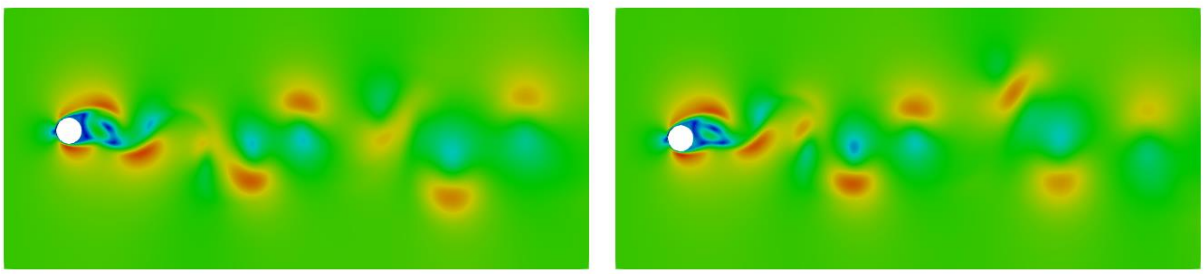


Figure 8. Streamlines at $T = 8.1$ seconds.

The velocity magnitude contour at $T = 32$ seconds is shown in fig. 9a.



(a) (b)

Figure 9. Velocity magnitude contours at; (a) $T = 32$ seconds; (b) $T = 27.5$ seconds.

The figure clearly shows a vortex that is about to be shed from the top of the cylinder, vortex generated and a vortex detached from the bottom half of the cylinder along with the already shed vortices at previous times.

The velocity magnitude contour at $T = 27.5$ seconds is shown in fig. $9b$. On comparison, it is clear that the phenomenon is periodic. Investigation on the periodicity of vortex shedding and its dependence on the frequency of oscillation is beyond the scope of this case study. The details can be found in references [3] and [4].

5. Conclusion

The laminar flow across an oscillating cylinder was simulated using OpenFOAM solver pimpleDyMFoam. The problem was simulated on a dynamic mesh which was solved using displacementLaplacian solver. The simulation produced expected result. The phenomenon of vortex shedding was observed. The simulation also indicated the periodicity of the phenomenon. The onset of vortex generation was shown using the streamlines plot in the immediate wake of the cylinder.

References

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