Visualization of vortex flow field around a flat plate with noncircular hole

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Abstract. In this paper we study the numerical three dimensional simulation of laminar incompressible viscous flow over a flat plate with circular and noncircular hole. The hole is located at the center of the plate. The aim of this paper is to visualize the steady and unsteady vortex dynamics using immersed boundary method. This method takes three variables, viz. velocity, vortices and the pressure to solve the flow field over a specimen. The plate considered is of 0.01 m length and the air is used as the flow medium and hole is made of same area. The analysis are done both circular hole plate and non-circular hole to examine the difference in the force and wake at the trailing part of the flat plate. In this study we measure the magnitude of vortices behind a flat plate and we also study the physical backdrop of how vortex strength is depend on the inner profile of the body. From the results it is evident that the reverse flow is stronger in non circular profile however the strength of vortex is higher in circular holed plate. It’s also found that velocity is inversely proportional to strength of vortices in flat plate with noncircular hole.

1. Introduction

Vortices helpful for various applications. It also plays negative role in some devices. For example in aircraft the wingtip vortices create a pressure drag called vortex drag which affects the performance of the aircraft by increasing the total drag on airplane. This vortex drag increases as the aircraft expels forward direction. As the aircraft manoeuvres these vortices turns stronger which induces the strong vortex drag. These vortices are controlled by placing winglets at the tip section of the wing part. The wingtip vortices grab energy from the forward motion of aircraft to create vortex drag. These vortices can be visualized in naked eye when wing tip vortices condense into visible trails of mist. Von Karman sheet give us the better clarity on the flow behind any bluff bodies at certain Reynolds number [1, 2, 3]. The strength of the vortices is depend on Re and the Re depend on the viscosity of fluid. If viscosity increases the vortices will be weak. The excessive vibration due to vortex shedding causes an aero elastic flutter and instability of the vortex. Kevin Helmholtz instability takes place when dynamic flow passes over a stationary plate. It helps to study the dynamics of two fluids at different density.

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This instability specified by Taylor goldstein equation [4] and Richardson number. The mixing of fluid are effectively done by generation of vortices, the combustion chamber is the best example. To gain the knowledge lets approach to the problem, flow over a flat plate in varies Reynolds number 40 to 4000 was visualized. The investigation carried for two cases with circular and non circular hole on a plate.

2. Simulation Methodology

Three dimensional incompressible flows over a flat plate with circular and non circular hole are simulated with a conventional immersed boundary method. The arbitrary geometry is generated in the flow by applying boundary method and boundary force [10, 9, 8]. Momentum equation of the system is assumed with boundary force to provide high resolution flow field. Navier strokes equation of incompressible flow is considered as

$$\frac{\partial u}{\partial t} + u \nabla u = -\nabla p + \frac{1}{Re} \nabla ^2 u + \int_0^\delta f(s,t) \delta(\hat{o} - x) ds$$

(1)

$$\nabla u = 0$$

(2)

$$u(s,t) = \int_0^\delta u(x) \delta(x-\hat{o}) dx = u(s,t)$$

(3)

Where u, p, f are velocity, pressure and surface force of the flow field. The x and ε are the spatial variables, x is known as domain variable and ε is the immersed boundary variable. Ub is the immersed boundary velocity.

Reynolds number of the fluid flow given by

$$Re = \frac{\rho uL}{\mu}$$

(4)

U is the free stream velocity, L is the length of the plate and μ is the kinematic viscosity of the fluid

Forces acting on the plate are lift, drag and weight, these three forces have an inertia frame of Fx, Fy and Fz

$$C_L = \frac{F_y}{0.5* \rho v^2 s}$$

(5)

$$C_d = \frac{F_x}{0.5* \rho v^2 s}$$

(6)

$$C_s = \frac{F_z}{0.5* \rho v^2 s}$$

(7)

3. Simulation setup

Simulation is performed in a rectangular domain of 1 X 0.5 in the stream wise of x axis. Inlet and outlet are defined in a domain with the velocity of 10m/s and the pressure of 1atm, other parts of the domain named as wall with slip. The flat plate with circular and noncircular hole immersed in the
domain and the boundary condition of wall is taken without slip. The plate is made of Kevlar composites [13, 15, 9, 8]. Grid size of the model is 100 x 20 x 60 to 200 x 80 x 120 with the highest resolution of $\Delta x=0.5$ for this case of aspect ratio 1.5. Grid is made finer at the rear part of the flat plate to capture the wake resolution in finer resolution. Boundary conditions of all side said to be uniform except the outlet of the domain.

4. Results and discussion

The specimen is well positioned at centre of the domain and investigation done on two cases flat plate with circular and non circular hole. The flow is assumed to be steady, segregated and isothermal process. Data and plots are taken from the post processing and there are compared for the study.

![Figure 1. Comparative plot data of Velocity and pressure](image-url)

Table 1. Flat plate with circular hole

| Velocity m/s | Pressure Pa | Vorticity rad/s |
|--------------|-------------|-----------------|
| 5.7          | 0.7         | 36.3            |
| 6.0          | 0.7         | 34.2            |
| 5.5          | 1.2         | 41.6            |
| 5.3          | 1.7         | 44.5            |
| 4.8          | 1.9         | 38.4            |
| 4.7          | 2.6         | 33.7            |
| 4.1          | 2.4         | 34.7            |
| 3.8          | 2.3         | 64.1            |
| 3.5          | 2.3         | 57.4            |
Figure 2. Comparative plot data of velocity and vortices

Fig 3. Vortex behind flat plate with circular hole
Fig 4. Pressure contour on flat plate with circular hole

Fig 5. Vortices at outlet of domain with circular hole
Fig 6. Pressure at outlet of domain with circular hole
Figure 7. Vortex behind flat plate with circular hole

Figure 8. Pressure on flat plate with non-circular hole

Figure 9. Vortices at outlet with non-circular hole

Figure 10. Pressure outlet of domain with non-circular hole

Table 2. Flat plate with circular hole

| Velocity m/s | Pressure Pa | Vorticity rad/s |
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| 4.7          | 2.6         | 33.7            |
| 4.1          | 2.4         | 34.7            |
| 3.8          | 2.3         | 64.1            |
| 3.5          | 2.3         | 57.4            |
Figure 11. Comparative plot data of ultimate stress due to compression stress

Figure 12. Comparative plot data of ultimate stress due to compression stress

Table 1 and 2 shows the magnitude of the vortices and the pressure when the flow medium passed through the flat plate at different velocity range. Figure 1 and 2 gives the plot of the table 1 and table 2. From this plot it is clear that the strength of vortex for circular profile is different from non-circular profiles. Magnitude of vortices is higher in circular hole when compared to non-circular hole due to the consistency in the shape of the profile. Figure 3 and 7 explains the flow of vortex behind the flat plate. In non-circular hole the formation is wake is high hence the strength of vortex is low. The figure 4-10 explains the shows different contours like pressure and velocity.

5. Conclusion
The results and plots show that the efficiency vortex is high in circular hole when compared to the non-circular profile. From the results it is evident that the non-circular hole can be applied to the system to produce vortices at low Reynolds number. It also found that

- The strength of the vortex is depending on the velocity of the flow medium.
- In circular hole, the velocity is directly proportional to the strength of vortices.
- In non-circular hole, the velocity is inversely proportional to the magnitude of the vortices.
- Reverse flow is stronger in non-circular profile.
- The pressure is independent with the vortices formation behind the flat plate.

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