Validation 3. Laminar Flow Around a Circular Cylinder

3.1 Introduction

Steady and unsteady laminar flow behind a circular cylinder, representing flow around bluff bodies, has been subjected to numerous experimental and computational studies. Most of the experimental studies are based on flow visualization and they indicate that as the Reynolds number $Re$ increases, the flow shows a series of different structures [1]. One of the most prominent flow structure changes takes place in the vicinity of $Re = 40$. Below this Reynolds number, the flow is steady and characterized by the presence of a symmetric pair of closed separation bubbles. Beyond $Re = 40$, the flow becomes unsteady and asymmetric, and alternate vortex shedding begins.

3.2 Purpose

The purpose of this test is to validate FLUENT’s ability to predict the flow structure as well as the reattachment length and Strouhal number against experimental results. The present calculations were confined to the low-Reynolds-number regime ($Re = 20$, $Re = 40$, and $Re = 100$), which encompasses steady symmetrical separated flow as well as unsteady asymmetric flow. The results were compared with the flow visualizations presented in [1] and the experimental data in [2].

3.3 Problem Description

An infinitely long circular cylinder of diameter $D = 2.0$ m is placed in an otherwise undisturbed uniform crossflow ($U_\infty = 1.0$ m/s) as shown in Figure 3.3.1. The lateral boundary and the exit boundary in the far wake are placed at $5D$ and $20D$ from the center of the circular cylinder, respectively.

3.3.1 Fluid Properties

The properties of the fluid are assumed to be constant, as shown in Table 3.3.1.

3.3.2 Flow Physics

The Reynolds number is based on the cylinder diameter and the free stream velocity. Different values of $Re$ (20, 40, 100) in the simulation were obtained by changing the viscosity.
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Figure 3.3.1: Problem Description

Table 3.3.1: Fluid Properties

<table>
<thead>
<tr>
<th>Reynolds No., $Re$</th>
<th>20</th>
<th>40</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, $\rho$</td>
<td>1 kg/m$^3$</td>
<td>1 kg/m$^3$</td>
<td>1 kg/m$^3$</td>
</tr>
<tr>
<td>Viscosity, $\mu$</td>
<td>0.1 Pa-s</td>
<td>0.05 Pa-s</td>
<td>0.02 Pa-s</td>
</tr>
</tbody>
</table>

$$Re = \frac{\rho UD}{\mu} \quad (3.3-1)$$

The experimental Strouhal number for the $Re = 100$ case is 0.165, derived from [2] and defined as

$$S = \frac{D}{\tau U} \quad (3.3-2)$$

where $\tau$ is the period of the vortex shedding.

3.3.3 Boundary Conditions

The no-slip wall condition is applied to the cylinder wall. Uniform free stream conditions ($U_\infty = 1.0$ m/s) are applied at the inlet and lateral boundaries. The flow exit is treated as a zero-normal-gradient outlet boundary.

3.4 Grid

A $51 \times 51$ quadrilateral mesh was used in this validation study, and is shown in Figure 3.4.1.
3.5 Case Setup

The FLUENT case was set up using constant fluid properties and the boundary conditions described in Section 3.3. Three runs were made using different values of viscosity to yield three different Reynolds numbers ($Re = 20$, $40$, and $100$) as shown in Table 3.5.1.

<table>
<thead>
<tr>
<th>Run</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reynolds Number, $Re$</td>
<td>20</td>
<td>40</td>
<td>100</td>
</tr>
</tbody>
</table>

3.6 Calculation

The second-order discretization scheme was used throughout this study. The first two cases ($Re = 20$, $40$) were run for steady-state solutions and the third case ($Re = 100$) was modeled as transient with a time step of 0.2 s.

For velocity-pressure coupling, the SIMPLEC algorithm was used. When the SIMPLEC algorithm is used, the pressure under-relaxation is automatically increased to 1.0. (The setting for pressure under-relaxation is 0.3 when the default SIMPLE algorithm is used). Here the momentum under-relaxation has also been increased from 0.7 to 0.9 to yield better convergence.

To break the symmetry of the flow and eventually trigger the vortex shedding, artificial perturbation was applied. The flow was perturbed by patching a uniform $x$ velocity of 1 m/s in the upper half of the domain and 0 m/s in the lower half. This is done using a custom field function defined as

$$u = \frac{y + |y|}{2y}$$  \hspace{1cm} (3.6-1)
where $u$ is the $x$ velocity.

This custom field function is saved in the case file with the name `initialvelocity`. After initializing the flow, the $x$ velocity of the entire fluid zone must be patched with this custom field function.

It should be noted that the use of artificial perturbation is not mandatory. It was applied here to expedite the symmetry breaking and subsequent vortex shedding.

### 3.7 Results

#### 3.7.1 $Re = 20$ and $Re = 40$

The near-wake contours of stream function and the velocity vectors for the $Re = 20$ and $Re = 40$ cases are shown in Figures 3.7.1–3.7.4. The flows are seen to be practically symmetric.

The reattachment length is measured from the downstream side of the cylinder to the point where the $x$ velocity changes sign from negative to positive. In this FLUENT model, a line named `centerline` and aligned with the $x$ axis was created. XY plots of $x$ velocity along the `centerline` are shown in Figures 3.7.5 and 3.7.6. The reattachment lengths, normalized by the cylinder radius ($R = 1$ m), are shown in Table 3.7.1.

Figure 3.7.7, which was taken from [2], shows the time evolution of the reattachment length collected from various sources. The present results are seen to agree fairly well with the data from [2].

<table>
<thead>
<tr>
<th>$L_A$</th>
<th>$Re = 20$</th>
<th>$Re = 40$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.85</td>
<td>4.27</td>
</tr>
</tbody>
</table>

#### 3.7.2 $Re = 100$

Figures 3.7.8–3.7.17 show the instantaneous velocity vector field and the corresponding streamlines at the five phases during one cycle of the vortex shedding. The alternate formation, convection, and diffusion of the vortices are clearly seen. To quantify the periodicity of the flow, the time history of the $y$ velocity at a point situated 1 m behind the cylinder in the near wake $(x, y) = (2, 0)$ was recorded and is shown in Figure 3.7.18. The average period was found to be $\tau = 12.1$ s, which is equivalent to a Strouhal number of 0.165. Figure 3.7.19, taken from [2], shows a collection of data from many sources on the Strouhal number vs. Reynolds number relationship. The FLUENT result agrees well with an average of the data shown in the figure.
3.7 Results

Figure 3.7.1: Stream Function Contours in the Wake ($Re = 20$)

Figure 3.7.2: Stream Function Contours in the Wake ($Re = 40$)
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Figure 3.7.3: Velocity Vectors in the Wake (Re = 20)

Figure 3.7.4: Velocity Vectors in the Wake (Re = 40)
3.7 Results

**Figure 3.7.5:** $x$ Velocity Along the Centerline ($Re = 20$)

**Figure 3.7.6:** $x$ Velocity Along the Centerline ($Re = 40$)
Figure 3.7.7: Reattachment Length vs. Time (from [2])
3.7 Results

Figure 3.7.8: Stream Function Contours in the Wake ($Re = 100, t = 42.2\text{ s}$)

Figure 3.7.9: Velocity Vectors in the Wake ($Re = 100, t = 42.2\text{ s}$)
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Figure 3.7.10: Stream Function Contours in the Wake ($Re = 100, t = 45.2$ s)

Figure 3.7.11: Velocity Vectors in the Wake ($Re = 100, t = 45.2$ s)
3.7 Results

Figure 3.7.12: Stream Function Contours in the Wake ($Re = 100$, $t = 48.2$ s)

Figure 3.7.13: Velocity Vectors in the Wake ($Re = 100$, $t = 48.2$ s)
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Figure 3.7.14: Stream Function Contours in the Wake ($Re = 100$, $t = 51.2$ s)

Figure 3.7.15: Velocity Vectors in the Wake ($Re = 100$, $t = 51.2$ s)
3.7 Results

Figure 3.7.16: Stream Function Contours in the Wake ($Re = 100, t = 54.6$ s)

Figure 3.7.17: Velocity Vectors in the Wake ($Re = 100, t = 54.6$ s)
Figure 3.7.18: $y$ Velocity History ($Re = 100$, $t = 42.2$ s)
3.8 Conclusion

FLUENT has been validated for a classical example of external flows around bluff bodies. The results agree fairly well with the data from various sources, in terms of the length of the recirculation region in the two steady cases ($Re = 20$, $Re = 40$), and the vortex shedding frequency in the unsteady case ($Re = 100$).

3.9 References
