A Fundamental Study of the Flow Past a Circular Cylinder Using Abaqus/CFD

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Introduction

- The release of Abaqus version 6.10 included Abaqus/CFD.
- The inclusion of this software makes it possible for users to perform a fluid analysis in a more user-friendly manner.

- Considering the role of fluid dynamics, the role can be categorized into the following functions;
  1. To understand actual fluid motion.
  2. To identify the flow-induced force acting on an object immersed in a fluid.
  3. To determine the fluid-structure interaction (FSI), i.e. the interaction of some movable or deformable structure with an internal or surrounding fluid flow.
- In relation to common aspects of mechanical design, II (flow-induced force) is the most practical target for exploiting CFD.
Flow past a circular cylinder

- From this viewpoint, the flow past a circular cylinder is the most basic problem.
  - The flow past a circular cylinder is classify are external flow.
  - The pattern of this flow varies depending upon the Reynolds number.

- In this study, we analyzed the following issues:
  - Variation in flow patterns corresponding to Reynolds number.
  - Interaction of structure and fluid flow.
  - The vibration of the cylinder by von Karman vortices.
Flow pattern depending on the Reynolds number

- The Reynolds number \((Re)\) is defined as follows;

\[
Re = \frac{\rho Ud}{\mu}
\]

\(\rho\) : Density  \(\mu\) : Coefficient of the viscosity

\(U\) : Characteristic velocity of flow  \(d\) : Diameter of the cylinder

- The flow pattern around a circular cylinder varies depending upon the Reynolds number.

- The shape of every streamline is symmetrical around the cylinder in a very small Reynolds number.
  (The upper photo is \(Re=0.038\))

- As Reynolds number increases and exceeds 60, von Karman vortex begins to occur.
  (The lower photo is \(Re=195\))

- In this study, we analyzed this problem within a range of Reynolds numbers up to 200 under which we considered it possible to analyze without turbulent modeling.

Analysis model

- The fluid was assumed to be water at room temperature.
  - The density was $\rho = 998 \text{ (kg/mm}^3\text{)}$.
  - The coefficient of viscosity was $\mu = 1.002E-03 \text{ (Pa} \cdot \text{sec)}$.

- The cylinder diameter was $d = 8 \text{ mm}$.

- A sufficiently extended analysis region was employed*.
  - 5d upstream, 15d downstream and 10d lateral direction.

- In Abaqus/CFD, three-dimensional fluid elements are available.
  - FC3D8: the eight-node brick fluid element

Boundary conditions

- On the inflow boundary, a uniform velocity was assigned to the x-direction.
  - The inflow velocity was obtained based on the Reynolds number.

- A non slip condition was provided on the surface of the cylinder.
  - I.E. all components of the velocity were zero.

- Zero pressure was applied to the outflow boundary in this analysis.

- The zero component of the velocity was intended to suppress outflow for the lateral boundaries.
Analytical results: Variation in flow patterns

- At a very low Reynolds number ($Re<1$), the flow pattern is symmetrical, from to back.
- At the Reynolds number increases a pair of bound vortices appears in the wake.
- Eventually, with higher Reynolds numbers the vortices form a von Karman vortex street.

The streamline of experimental result (upper) and analytical result (lower)

Re = 0.038
Re = 1.1
Re = 195
Re = 26

The velocity contour of time change at $Re=195$
Analytical results: Drag force

Whenever object is placed in a fluid flow, a force in the flow direction (drag force) is observed. The drag force is the sum of the skin friction and the force due to the pressure on the body.

A drag coefficient \( C_D \) is defined as the ratio of the drag force \( F_x \) to half the inertial force:

\[
C_D = \frac{F_x}{0.5 \rho U^2 S}
\]

\( S \): Reference area

For low Reynolds number, drag coefficient decreases as the Reynolds number increase. Because basically the drag force is due to viscous forces.

At Re>100 the drag coefficient becomes about constant.

Analytical results: Strouhal number

- Strouhal number is a dimensionless number used to describe oscillating flow mechanisms. The frequency of the von Karman vortices was possible to estimate by the Strouhal number.

- The Strouhal number \((St)\) is given as:

\[
St = \frac{f \times d}{U}
\]

- Rayleigh established the Strouhal number as a function of the Reynolds number;

\[
St = 0.195 \times \left(1 - \frac{20.1}{Re}\right)
\]

- The difference in the analysis and the experiments was due to acceleration caused by the lateral analysis region being finite.

Fluid-structure coupling problem

- Abaqus6.10 address a broad range of nonlinear coupled fluid-structural problems. So, a fluid-structure coupling problem was analyzed.

- The circular cylinder was modeled using hexahedral stress/displacement elements (C3D8R), and connected with springs in the y-direction while kept stationary in the x-direction.

- The material constants of the fluid were same as previous analysis, and the value of inflow velocity used 12.5mm/sec.
Fluid-structure coupling problem

- The natural frequency \( (f_n) \) of the spring can be expressed by the following formula.

\[
f_n = \frac{1}{2\pi} \sqrt{\frac{k}{m}}
\]

\( k \): Spring constant
\( m \): Mass of the cylinder

- The Strouhal number \( (St_n) \) in respect of this natural frequency is defined by the following formula.

\[
St_n = \frac{1}{2\pi} \frac{U}{f_n d}
\]

\( U \): Velocity of the flow
\( d \): Diameter of the cylinder

- In this analysis, although the flow rate was kept constant, the Strouhal number was varied by changing the spring constant.

- Ideally, the effect from the Reynolds number should be examined with changing flow rate, but this effect should be studied at a later stage.
Analytical results : Deformation

- The figures are fluid deformation diagram of analysis result of $St_n=0.7$.
- This Strouhal number was possible to analysis without turbulent condition.

Fluid deformation diagram of $St_n=0.7$

The magnified figure around circular cylinder.
Analytical results: Vibration frequency of cylinder

- The vibration frequency of the cylinder were obtained from the analysis. The frequencies were observed to be proportional to the Strouhal number.

- However, the experimental results were almost constant value within a range of $St_n = 0.8\sim1.15$. This phenomenon is called a lock-in phenomenon.

Variation in the vibration frequencies corresponding to each Strouhal number

Analytical results: Amplitudes

- In the lock-in region, the vibration amplitudes of the experimental results sharply increased, while the analytical results show a nearly-unchanged response by Strouhal number.

- The lock-in phenomenon may lead to a high possibility of the flow transitioning into turbulent flow. However, this study was largely limited to laminar flow.

Variation in the vibration amplitudes corresponding to each Strouhal number
Conclusions

- In the current study, fluid flows around a circular cylinder were analyzed for a region with Reynolds number up to 200. The analysis with turbulent region (i.e. Reynolds number over 200) is an issue in the future.

- Although we verified the basic capabilities with regard to coupled structural fluid analysis in this study, additional analyses are needed to verify more advanced features.


- Thank you very much for kind attention.
Analysis time of the flow past a circular cylinder

- Using a dual-core CPU, the analysis of Re=0.038 took about 1 min.
- The analysis time increased in proportion with the Reynolds number.
- And the analysis of Re=195 took about 140 min.

Variation of the analysis time with Reynolds number.

Left side: Reynolds number 1.1 or less
Right side: Reynolds number 5.0 to 195
Analysis time of structure-fluid coupling problem

- Also using a dual-core CPU, the analyses took about 275 min without depending on Strouhal number.
  - Because the analysis time depends on Reynolds number, and Reynolds number was constant in these analyses.

Variation of the analysis time with Strouhal number.
The inflow velocity

- On the inflow boundary, a uniform velocity was assigned to the x-direction. The inflow velocity was obtained based on the Reynolds number.

- The fluid was assumed to be water at 293K where the density was $\rho = 998.204$ (kg/mm³) and the coefficient of viscosity was $\mu = 1.002 \times 10^{-3}$ (Pa · sec).

- Therefore, to verify variation in flow patterns corresponding to various Reynolds numbers, the table below provides the inflow velocities.

<table>
<thead>
<tr>
<th>CASE</th>
<th>Reynolds number [ - ]</th>
<th>Inflow velocity [mm/ sec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CASE 1</td>
<td>0.038</td>
<td>4.77E-03</td>
</tr>
<tr>
<td>CASE 2</td>
<td>1.1</td>
<td>0.138</td>
</tr>
<tr>
<td>CASE 3</td>
<td>26</td>
<td>3.26</td>
</tr>
<tr>
<td>CASE 4</td>
<td>50</td>
<td>6.27</td>
</tr>
<tr>
<td>CASE 5</td>
<td>100</td>
<td>12.5</td>
</tr>
<tr>
<td>CASE 6</td>
<td>195</td>
<td>24.5</td>
</tr>
</tbody>
</table>

A water temperature of 293 K was assumed: $Re = \rho U d / \mu$
Analysis results 1 – Variation in flow patterns

- CASE 1 correspond to flows with a sufficiently low Reynolds number, and their streamlines appeared symmetrically, front to rear.
- Reynolds number of CASE 2 had exceeded 1, therefore the symmetry was lost in the front and rear flow.

The streamlines of $Re = 0.038$

The streamlines of $Re = 1.1$
Analysis results 1 – Variation in flow patterns

- In CASE 3 and CASE 4, Reynolds numbers were each 26 and 50, and a pair of upper and lower vortices was generated within the wake of the cylinder.

- As the Reynolds number increased, the vortex expanded and increased in length.

The streamlines of Re = 26

The streamlines of Re = 50
Analysis results 1 – Variation in flow patterns

- In CASE 5 and CASE 6, Reynolds numbers exceeded 100, the von Karman vortex street occurred.
- When the Reynolds number was higher, the von Karman vortices lasted for a shorter period.

The velocity of Re = 100

The velocity of Re = 195
Analytical results : Flow separation

- The behavior of flow separation in $Re = 50$ was verified.

- The reverse flow region occurs behind a point of flow separation. As in figure of shown flow velocity vector, the point was an angle about 130 deg, measuring the angle clockwise stating from the center of the front edge of the cylinder.

- The wall shear stress become zero at the separation point. If we saw the distributions of wall’s shear stress at the angle of 0~180 deg, this point was about 130 deg.

Flow velocity vector of $Re = 50$ in the vicinity of the cylinder

The wall’s shear stress of $Re = 50$
Time history curves of fluid force

- The focus was on steady state flow. However the analysis was unsteady state flow. So, the analysis of unsteady state flow should be carried out stating from time zero and proceeding until a steady state flow is reached.

- With a lower Reynolds number, the fluid force simply reaches stationary state.

- Whereas in the presence of the Karman vortices, the fluid force was observed on one occasion to decrease substantially and the return to a stationary state.

The time history curves of fluid force of Re = 0.038

The time history curves of fluid force of Re = 195
The spring constants

The spring constants is obtained by following equation.

\[ St_n = \frac{1}{2\pi \frac{U}{f_n d}} = \frac{U}{d} \sqrt{\frac{m}{k}} \]

- **St**: Strouhal number [ - ]
- **U**: velocity of the flow ( = 12.5 [mm/sec])
- **f_n**: frequency of the flow
- **m**: mass of the cylinder ( = 3.95E-07 [ton])
- **d**: diameter of the cylinder ( = 8 [mm])
- **k**: spring constant

Values shown in following table were applied to the spring constants of the spring.

| CASE 1 | 0.7 | 1.98E-06 |
| CASE 2 | 0.8 | 1.52E-06 |
| CASE 3 | 0.9 | 1.20E-06 |
| CASE 4 | 1.0 | 9.71E-07 |
| CASE 5 | 1.1 | 8.02E-07 |
| CASE 6 | 1.2 | 6.74E-07 |