EFFECTS OF A MOVING MEMBRANE ON THE WAKE BEHAVIOR OF A CIRCULAR CYLINDER

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ABSTRACT
The aim of this paper is to investigate a novel technique to control the flow around a circular cylinder. This technique consists of putting a moving membrane stuck to the cylinder. The commercial software Ansys fluent 16.0 is used. The motion of the moving membrane is governed by a user-defined function. The numerical simulation is performed for the Reynolds number equal to Re=150. By changing the frequency of the oscillating membrane from f=0.1Hz to f=6.0Hz, we found that the drag coefficient is significantly affected and its curve shows a beat phenomenon for f around 4.5 Hz.

INTRODUCTION
Flow around bluff bodies has been a topical issue for many research fields, especially in aerodynamic, such as flow around tanks, chimneys, aircrafts. Researchers strive to find novel techniques to enhance the aerodynamic performance of vehicles as it pertains to speed and fuel efficiency. The active flow control (AFC) consists of putting actuators on the surface of bluff bodies to modify the flow. One of the most important techniques of active control is the synthetic jet. The synthetic jet is being generated due to a periodic motion of a membrane. The fluid inside the cavity is pumped up and down through an orifice and then it interacts with the rest of the fluid leading to a fluid flow modification. Many parameters are studied to enhance the aerodynamic forces such as the velocity of the synthetic jet and geometric parameters of the orifice [1]. Basharat et al. [2] studied numerically the effects of the synthetic jet actuator around a thick NASA GA (W)-2 airfoil at Re=2.1x10⁵. The actuator is located at a distance, which is 13% of the chord from the leading edge, and the study is done for varied angles of attack. Their results showed an increase in the lift coefficient and a decrease in the drag coefficient compared to the ones obtained in the uncontrolled case. Bera et al. [3] investigated experimentally a jet oscillation around a circular cylinder with a Reynolds number Re =1.33x10⁵. They placed an acoustic actuator with an electrical feed of frequency f=200Hz at 110° relative to the stagnation point. Their results show a modification of the aerodynamic forces compared with those obtained in -uncontrolled case. The high-level control was obtained with a jet velocity equal to 42m/s. To reveal the impact of the position and number of the actuator points, Li et al. [4] have controlled experimentally (PIV technique) the vortex around a circular cylinder at a Reynolds number equal to 950 using a synthetic jet positioned at the rear stagnation point with a frequency between 1.67 and 5.00 times than the natural shedding frequency. Their results show a conversion of the wake-vortex from the anti-symmetric mode to the symmetric one. The rear-stagnation-point rather than the near separation one induces the control effect. Inspired from bio fly, Wei et al. [5] studied numerically the effect of a local oscillating membrane attached to an airfoil NACA 0012 with an attack angle of 6° at a Reynolds number equal to 5000. Their parametric study was based on frequency, amplitude and the pre-deformed equilibrium of the oscillation of this flexible membrane. They found that the frequency is the most important parameter to enhance the lift coefficient. For f = 1.22Hz, the lift variation ratio reaches 69.86 % compared to the uncontrolled case. The simulation of the moving membrane motion is more realistic with a dynamic mesh than velocity inlet since its capability to follow the grid change near the moving membrane [6]. In the present work, a moving membrane is attached to a circular cylinder and from the same side of the wake is used as an active control method. A parametric study of frequency effects on the fluid flow behaviour is done. The aerodynamic parameters such as drag and lift coefficient, Strouhal number are compared in each case with those obtained without control. The FLUENT 16.0 was chosen as a software and the motion of the membrane is controlled by a user-defined function.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>[N.m⁻²]</td>
<td>Local pressure</td>
</tr>
<tr>
<td>x</td>
<td>[m]</td>
<td>Cartesian axis</td>
</tr>
<tr>
<td>y</td>
<td>[m]</td>
<td>Cartesian axis</td>
</tr>
<tr>
<td>D</td>
<td>[m]</td>
<td>Diameter</td>
</tr>
<tr>
<td>̅u</td>
<td>[m.s⁻¹]</td>
<td>Fluid velocity</td>
</tr>
<tr>
<td>U∞</td>
<td>[m.s⁻¹]</td>
<td>Free stream velocity</td>
</tr>
<tr>
<td>ρ</td>
<td>[kg.m⁻³]</td>
<td>Fluid density</td>
</tr>
<tr>
<td>μ</td>
<td>[N.s.m⁻²]</td>
<td>Fluid viscosity</td>
</tr>
<tr>
<td>f</td>
<td>[Hz]</td>
<td>Frequency</td>
</tr>
<tr>
<td>A</td>
<td>[m]</td>
<td>Amplitude</td>
</tr>
<tr>
<td>St</td>
<td>[-]</td>
<td>Strouhal number</td>
</tr>
<tr>
<td>Re</td>
<td>[-]</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>̇u/̇t</td>
<td>[m.s⁻²]</td>
<td>Acceleration</td>
</tr>
</tbody>
</table>
\( \frac{\partial^2 \vec{u}}{\partial t^2} \) \[\text{N.m}^{-1}\] local acceleration

\( \rho \frac{\partial (\vec{v} \cdot \vec{u})}{\partial t} \) \[\text{N.m}^{-1}\] Diffusion term

\( \mu \nabla (\nabla \vec{u}) \) \[\text{N.m}^{-1}\] Pressure gradient

\( k_n \) \[\text{N.m}^{-1}\] Spring factor

\( \vec{F}_x \) \[\text{N}\] Spring force

\( \Delta x_i \) \[\text{m}\] Displacement

\( C_{D_0} \) \[-\] Drag coefficient

\( F_D \) \[\text{N}\] Drag force

\( C_{L_2} \) \[-\] Lift coefficient

\( F_L \) \[\text{N}\] Lift force

Special characters

\( C_{D_{nk}} \) \[-\] Mean drag for natural frequency

\( C_{D_{nk}} \) \[-\] Mean drag for controlled frequency

\( r_{D} \) \[-\] Relative growth rate of drag

\( r_{L} \) \[-\] Relative growth rate of lift

EXTERNAL BOUNDARY CONDITIONS

Figure 1 presents the computational domain. The centre of the circular cylinder coincides with the origin of the coordinate system. The oncoming flow direction coincides with the x-axis. The top and bottom boundaries of the rectangular domain are set as walls and coincides respectively with \( y = +100 \text{ mm} \) and \( y = -100 \text{ mm} \). The inlet is set at Reynolds number equal to 150. The outlet is set at pressure outlet with zero gauge pressure. The distance between the inlet and the outlet is 700mm. We have used GAMBIT as software to model and generate structured and unstructured mesh generating 128543 cells. A refinement of the surface close the moving membrane is done.

![Figure 1 Model of circular cylinder with a locally oscillating surface](image)

GOVERNING EQUATIONS

Governing equations of unsteady viscous flow are defined as follows:

Conservation of mass:

\[ \nabla \cdot \vec{u} = 0 \]  

Conservation of momentum:

\[ \frac{\partial \vec{u}}{\partial t} = -\nabla p + \rho \nabla \cdot (\vec{u} \nabla \vec{u}) + \mu \nabla (\nabla \vec{u}) \]  

The spatial discretization method is second order upwind for the momentum and second order for pressure. The time step used in the present study is equal to 0.005. The motion is governed by the following equation:

\[ x = A \cos(3000 \pi y) \sin(2 \pi f \cdot t) + \sqrt{(R^2 - y^2)} \]  

Where:

\( R = 0.0075 \text{m} \) Radius of the circular cylinder

\( A = 0.001 \text{m} \) The amplitude of the membrane’s motion

\( f (\text{Hz}) \) Frequency of the moving membrane

The parametric study is simulated for different values of frequency and with a constant amplitude \( A = 0.001 \). In figure2, we showed the moving membrane with an angle of aperture of 8° moving periodically with an amplitude \( A = 0.001 \) m and \( f = 0.5 \) Hz leading to a modification in the near structure of the mesh. The grid is remeshed each iteration near the moving membrane since that the connectivity between nodes is as a network of springs. With a Hooke’s law, a spring force \( F_i \) is applied for each displacement at a boundary node.

\[ F_i = \sum_j k_i \left( \Delta x_j^i - \Delta x_j^i \right) \]  

Where \( \Delta x_j^i \), \( \Delta x_j^i \) are the displacements of node i and its neighbor j.

\( n_i \) The number of nodes connected to i

\[ k_i = \frac{k_{fac}}{|n_i|} \]  

\( k_{fac} \): The spring factor is between 0 and 1.

![Figure 2 Dynamic mesh of moving membrane f=0.5 Hz and A=0.001m](image)

VALIDATION OF NUMERICAL MODELS

The drag and lift coefficients are given respectively by these equations:

\[ C_D = \frac{F_D}{0.5 \rho U_\infty^2 D} \]  

\[ C_L = \frac{F_L}{0.5 \rho U_\infty^2 D} \]  

The Strouhal number is given by:

\[ St = \frac{f_i D}{U_\infty} \]  

where \( f_i \) is the natural frequency of the vortex shedding. To validate the user defined function controlling the motion of the moving membrane, we set the value of moving membrane frequency \( f \) equal to \( 10^6 \text{Hz} \) as a reference value since...
the membrane seems static. Therefore, we must have the same values of the aerodynamic forces in the uncontrolled case. Figure 3 presents the periodic fluctuations of the lift coefficient. Figure 4 presents the spectral decomposition of y velocity magnitude of a point from the shedding vortex. The maximum is observed for \( \text{St} = 0.1944 \). Results presented in table 1 show a good agreement with published ones.

![Figure 3](image)

**Figure 3** Time history of lift coefficient at \( \text{Re} = 150 \)

![Figure 4](image)

**Figure 4** Strouhal number for \( \text{Re}=150 \)

<table>
<thead>
<tr>
<th>Aerodynamic Parameters</th>
<th>Rahman et al. (2012)</th>
<th>Uncontrolled case</th>
<th>Controlled case with ( f = 10^{-9} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strouhal number ( S_t )</td>
<td>0.1872</td>
<td>0.1955</td>
<td>0.1944</td>
</tr>
<tr>
<td>Max ( C_l )</td>
<td>0.5014</td>
<td>0.5173</td>
<td>0.5169</td>
</tr>
</tbody>
</table>

**Table 1** Comparison of \( S_t \) and max \( C_l \) values with those of Rahman et al.

![Figure 5](image)

**Figure 5** Contours of velocity and Von Karman shedding

From figure 3, we observed that the periodic pressure variation on the cylinder surface induces the formation of periodic shedding in the backside as shown in figure5. In entrance, the fluid has a steady behaviour. After contacting the cylinder, the wake becomes unstable and shed alternately behind the bluff body. The vortices show an antisymmetric structure. The maximum of velocity is observed on the stagnation points. The aim of the control in this study is to study the influence of a perturbation of wake by the introduction of a moving membrane attached at the rear point of the cylinder.

**ACTIVE CONTROL AND FREQUENCY INFLUENCE**

We run different cases of simulation for frequency \( f \) varies between 0.1Hz and \( f=6.0Hz \). To study the sensibility of the frequency’s variation \( f \) on the aerodynamic forces, we have calculated the relative growth rate defined as follows:

\[
\frac{\Delta C_d}{C_d} = \frac{C_d(f) - C_d}{C_d},
\]

\[
\frac{\Delta C_l}{C_l} = \frac{C_l(f) - C_l}{C_l}.
\]

Were:

\( \Delta C_d = C_d(f) - C_d \) is the variation of mean drag value

\( \Delta C_l = C_l(f) - C_l \) is the variation of lift value

<table>
<thead>
<tr>
<th>( f_i )</th>
<th>( \frac{\Delta C_d}{C_d} )</th>
<th>( \frac{\Delta C_l}{C_l} )</th>
</tr>
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<tbody>
<tr>
<td>0.1</td>
<td>3.72</td>
<td>2.515</td>
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<tr>
<td>0.2</td>
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<td>1.444</td>
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</tr>
<tr>
<td>6</td>
<td>1.44</td>
<td>6.087</td>
</tr>
</tbody>
</table>

**Table 2** Influence of frequency of the membrane on the drag and lift growth rate

For frequencies between 0.1 Hz and 0.8 Hz, the lift coefficient increase from 2% to 4.91%. For frequencies between 1.7 Hz to 6.0 Hz, we cannot expect a constant variation of lift coefficient since it varies from one value to another. For the drag, its growth rate periodically increase and decrease from one frequency to another. Therefore, we can expect that the drag is more sensitive to the motion of the moving membrane since it is positioned laterally.
Figure 6 Time history of drag and lift for different frequency of the moving membrane
Results and discussions

Figure 6 shows the time history of drag and lift coefficients for different frequency of moving membrane. As it can be seen, the drag coefficient is more affected by the lateral motion of the moving membrane. A beat phenomena are clearly observed on its curve for $f=4.5$ Hz at the amplitude equal to 0.001. The two frequencies are $f_{b1} = 3.8654$ Hz and $f_{b2} = 4.4999$ Hz. We notice that $f_{b1}$ is exactly the frequency of the moving membrane. The natural vortex frequency is $f=1.93$. As the period of the lift is double than the drag, so the frequency of the drag without control is $f=1.93 \times 2 = f_{b2}$. Each frequency is responsible of the apparition of a wake. $f_{b1}$ and $f_{b2}$ are extremely close, we can expect the beat phenomena that has been observed. (figure 7).

CONCLUSION

A numerical study at $Re=150$ is investigated to study the effect of the moving membrane frequency in controlling the wake behind a circular cylinder. A parametric study of the dependence of drag and lift history for a plage of frequency $f$ between 0.1 and 6 Hz at a fixed amplitude $A=0.001$ m is done. At $f=4.5$ a beat phenomena are observed in the drag history. This phenomena know before as drag crisis was observed only for turbulence in uncontrolled case. For active control a similar phenomenon was observed for the lift coefficient. The periodic motion of the moving membrane generated a new wake close to it. The interaction of the natural wake with the forced one leads to the beat phenomenon.

References