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

Maktouf N.* Ben moussa A. and Turki S.

Sfax University.
National engineering school of Sfax Tunisia ENIS,
Computational Fluid Dynamics and Transfer Phenomena
Sfax, 3038,
TUNISIA,
E-mail: nabaouia.maktouf@ipeis.rnu.tn

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 aircrafts 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=2.1x10^6. 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 =1.33x10^5.They placed an acoustic actuator with an electrical feed of frequency f=200Hzat 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

P	[N.m^{-2}]	Local pressure
x	[m]	Cartesian axis direction
y	[m]	Cartesian axis direction
D	[m]	Diameter
$\vec{u}$	[m.s^{-1}]	Fluid velocity
U_∞	[m.s^{-1}]	Free stream velocity
ρ	[kg.m^{-3}]	Fluid density
μ	[N.s.m^{-2}]	Fluid viscosity
f	[Hz]	Frequency
A	[m]	Amplitude
S_t	[-]	Strouhal number
Re	[-]	Reynolds number
$\dfrac{\partial \vec{u}}{\partial t}$	[m.s^{-2}]	Acceleration

$\rho\dfrac{\partial\vec{u}}{\partial t}$	[N.m^{-3}]	local acceleration
$\mu\nabla.(\nabla\vec{u})$	[N.m^{-3}]	Diffusion term
∇p	[Pa.m^{-1}]	Pressure gradient
k_{ij}	[N.m^{-1}]	Spring factor
$\vec{F_i}$	[N]	Spring force
$\Delta\vec{x_i}$	[m]	Displacement
C_D	[-]	Drag coefficient
F_D	[N]	Drag force
C_L	[-]	Lift coefficient
F_L	[N]	Lift force
Special characters		
$\overline{C_{d_0}}$	[-]	Mean drag for natural frequency
$\overline{C_{df_i}}$	[-]	Mean drag for controlled frequency
r_{C_d}	[-]	Relative growth rate of drag
r_{Cl}	[-]	Relative growth rate of lift

EXTERNAL BOUNDARY CONDITIONS

Figure1 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 mm and y = -100mm. The velocity 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 instructed mesh generating 128543 cells. A refinement of the surface close the moving membrane is done.
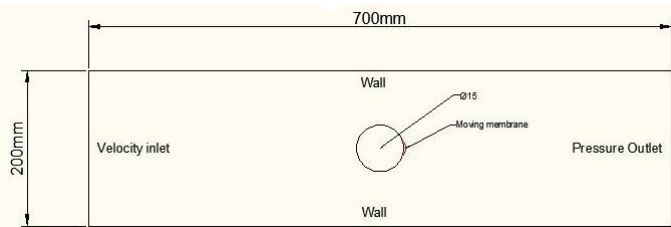

Figure 1 Model of circular cylinder with a locally oscillating surface

GOVERNING EQUATIONS

Governing equations of unsteady viscous flow are defined as follows:
Conservation of mass:

$$\nabla.\vec{u} = 0 \qquad (1)$$

Conservation of momentum:

$$\varphi\frac{\partial\vec{u}}{\partial t} = -\nabla p - \varphi\vec{u}.\nabla\vec{u} + \mu\nabla.(\nabla\vec{u}) \qquad (2)$$

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:

$$x = A\cos(3000\,y)\sin(2\pi f\ t) + \sqrt{(R^2 - y^2)} \qquad (3)$$

Where:

R=0.0075m	Radius of the circular cylinder
A=0.001m	The amplitude of the membrane's motion
f(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 model of Hooke's law, a spring force $\vec{F_i}$ is applied for each displacement at a boundary node.

$$\vec{F_i} = \sum_{j}^{n_i} k_{ij}\left(\Delta\vec{x_j} - \Delta\vec{x_i}\right) \qquad (4)$$

Where $\Delta\vec{x_j}$, $\Delta\vec{x_i}$ are the displacements of node i and its neighbor j.
n_i The number of nodes connected to i

$$k_{ij} = \frac{k_{fac}}{\sqrt{\left|\vec{x_i} - \vec{x_j}\right|}}$$

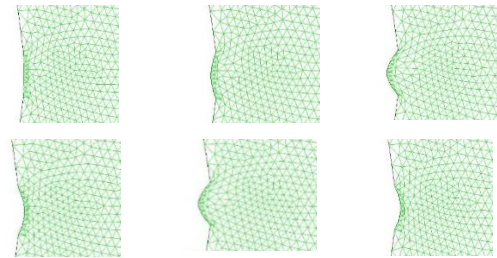k_{fac} : The spring factor is between 0 and 1.

Figure 2 Dynamic mesh of moving membrane f=0.5 Hz and A=0.001m

VALIDATION OF NUMERICAL MODELS

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

$$C_D = \frac{F_D}{0.5\rho U_\infty^2 D} \quad (7), \qquad C_L = \frac{F_L}{0.5\rho U_\infty^2 D} \quad (8)$$

The Strouhal number is given by:

$$St = \frac{f_0 D}{U_\infty} \quad (9),$$ where f_0 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^{-9}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 St = 0.1944. Results presented in table 1 show a good agreement with published ones.
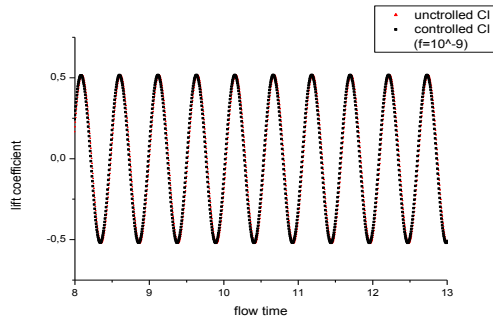

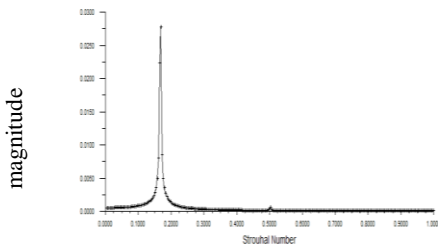**Figure 3** time history of lift coefficient at $R_e = 150$

Figure 4 Strouhal number for Re=150

Aerodynamic Parameters	Rahman et al. (2012)	Uncontrolled case	Controlled case with $f = 10^{-9}$
Strouhal number S_t	0.1872	0.1955	0.1944
Max C_l	0.5014	0.5173	0.5169

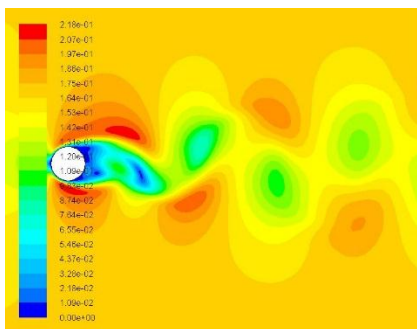**Table 1** Comparison of St and max C_l values with those of Rahman et al.

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 <u>in</u> 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 <u>of</u> on the aerodynamic forces, we have e calculated the relative growth rate defined as follows:

$$r_{C_d} = \frac{\Delta \overline{C_{df_i}}}{\overline{C_{d_0}}} . \qquad r_{Cl} = \frac{\Delta \overline{C_{lf_i}}}{\overline{C_{l_0}}}$$

Were:

$\Delta \overline{C_{df_i}} = \overline{C_{df_i}} - \overline{C_{d_0}}$ is the variation of mean drag value

f_i	$r_{Cd}(\%)$	$r_{Cl}(\%)$
0.1	3.72	2.515
0.2	4.046	3.657
0.3	3.863	4.241
0.4	3.663	4.56
0.5	4.053	4.722
0.6	3.717	4.794
0.7	3.792	4.78
0.8	3.714	4.91
1.7042	3.06	4.759
2	2.284	3.839
3.8	1.444	6.949
4.5	1.651	5.123
5.5	2.742	5.643
6	1.44	6.087

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.
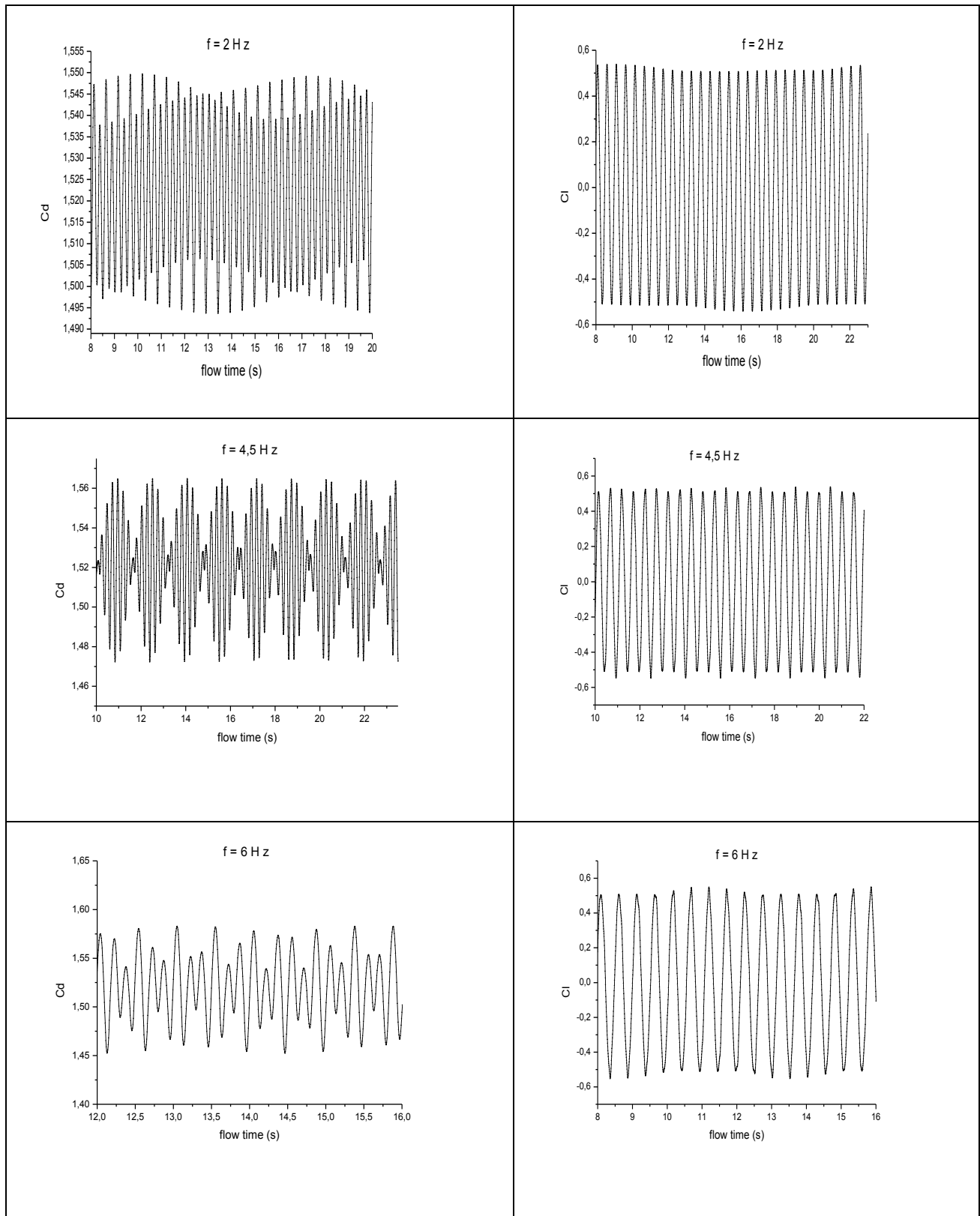
Figure 6 Time history of drag and lift for different frequency of the moving membrane

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 $f_{b2} = 3,8654$ Hz and $f_{b1} = 4,4999$ 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=1.93x2=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).
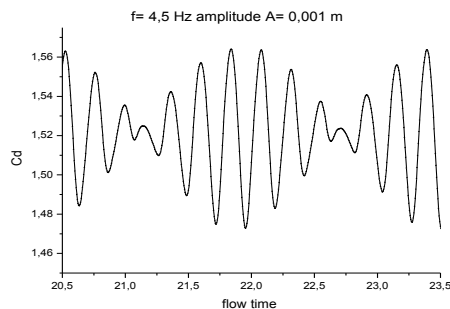

Figure7 Beat phenomenon for drag coefficient

A similar behaviour of drag was observed especially in turbulent case and without control by Andrei et al. [9] and named as Drag crisis. In case of active control, Jinsung et al. [10] has observed a beat phenomenon in the lift history due to two blowing suctions positioned in the same direction of the lift force. Their parametric study was performed for Re = 100 and for different spanwise wavelength of the disturbed force. We can expect that a beat phenomenon is observed for the aerodynamic force parallel to a perturbation. In fact and as it is shown in figure 8, the periodic motion of the moving membrane form a separated bubble close to it leading to an increase in the pressure distribution, while a pressure wave grows on the other side. The periodic motion of the membrane leads to a continuous generation and interaction of these waves.
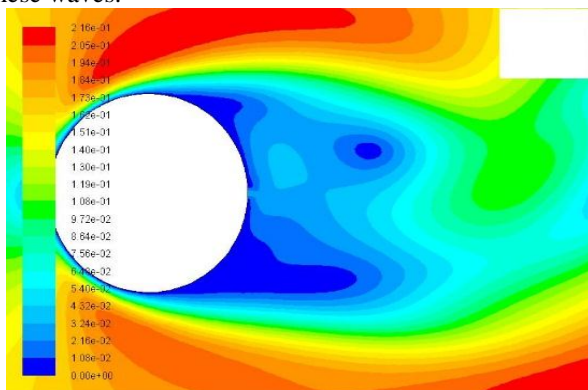

Figure 8A new vortex generated due to the motion of the moving membrane

CONCLUSION

A numerical study at R_e =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 areobserved 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 phenomemeon.

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