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Flow visualization and analysis of wake behind a sinusoidal cylinder

A.T. Nguyen* and S. J. Lee**

Abstract

The near wake behind a sinusoidal cylinder has been investigated quantitatively using hot-wire anemometer and qualitative. The mean velocity and turbulence intensity were measured in streamwise and spanwise direction. The results show that the wake in the saddle plane has a longer vortex formation region and rapid reversed flow than that in nodal plane. The elongated vortex formation region of sinusoidal cylinder is related with drag reduction. In addition, the flow visualized with particle tracing method support the flow characteristics of sinusoidal cylinder measured by hot-wire.

1. Introduction

Vortex shedding from a bluff body is a challenging area of fluid dynamic researches. For example, the large drag forces and possible vortex-induced vibration (VIV) of pipes and long slender tubular are important in design of offshore structures. There is several passive flow control technique to reduce drag force and suppress regular vortex shedding. These techniques use some form of three-dimensional geometric disturbance to the nominally 2-D bluff body, for instance, helical strakes, grooves, ribbons, bump …etc.

As a previous study, Bearman and Tombazis (1993, 1997) obtained 34% maximum drag reduction by introducing a blunt-based model with wavy trailing edge at Reynolds number of 40,000. They mentioned that the introduction of a spanwise waviness at the trailing edge could fix the position of vortex dislocation resulting to drag reduction. Bearman and Owen (1998) investigated the influence of spanwise waviness on flow around rectangular cross-section with sinusoidal form both in front and rear face. They obtained about 30% drag reduction, compared with equivalent straight body and announced the optimized ratio of peak to peak wave height dived by wavelength is between 0.06 and 0.09. Recently Lam et al (2003) experimentally investigated the near wake of a wavy cylinder using LDV and preliminary numerical simulation. The mentioned results indicate the important role of vortex formation length to drag reduction and suppressing vortex.

In this study, a sinusoidal cylinder (or wavy cylinder) was employed as a passive method to reduce drag force and vortex induced vibration (VIV). The mean velocity and turbulent intensity profiles in the near wake behind the wavy cylinders were experimentally investigated by using a hot-wire anemometer. In addition, flow field around the cylinders was visualized using particle tracing method to see the flow structure qualitatively. The results were compared with those for a smooth circular cylinder (normal circular cylinder) having the same diameter $D = D_m$.

* Dept.of Mech.Eng., POSTECH, anhtuan@postech.ac.kr
**Dept.of Mech.Eng., POSTECH, sjlee@postech.ac.kr

2. Experimental apparatus and methods

2.1 Model geometries

One circular cylinder and two sinusoidal cylinders were tested in the wind tunnel and water channel test. The terminology used for the sinusoidal cylinder is shown in Fig 1. The axial locations of maximum diameter are termed "geometric node" and that of minimum diameter is termed "geometric saddle". The geometry of the sinusoidal cylinder is described by the following equation:

$$D = D_m + 2W\cos(2\pi y/\lambda)$$

$$\frac{dD(y)}{dy} = \frac{W\pi}{\lambda}\sin\left(\frac{2\pi y}{\lambda}\right)$$

where D is the local diameter of sinusoidal cylinder, D_m = 20mm is the mean diameter of sinusoidal cylinder. In this study, the value of wave height W was fixed at W = 4m and two case of λ = D and 2D. Therefore, $\pi w/\lambda$ is the maximum magnitude of the slope and depend on W/λ defined as the *wave steepness* (Bearman and Owen 1998). This parameter plays important role in finding the optimal shape of sinusoidal cylinder, especially in computational anlysis.

2.2 Experimental methods

Drag force, mean velocity and turbulence intensity profile were measured in a closed-return type subsonic wind tunnel with a test section of 720x600 mm^2. The free stream turbulence intensity is less than 0.01% at U_0 = 10m/s. The flow structures around the cylinders were measured at Reynolds numbers based on D_m at Re = 5.3×10^3 and Re = 2.1×10^4.

Wake velocity profiles were measured using an I-type hot-wire probe (DANTEC 55P11). Hot-wire probe was traversed using a 3-D traverse system with an accuracy of 0.01 mm over the range z/D = –3 ~ 3 with an interval of $\Delta z = 1.5D$. At each measurement point, 32,768 velocity data were acquired at a rate of 2000 samples/s with a DT2838 A/D converter, after low-pass filtering at 800 Hz. The aerodynamic forces were measured using a 3-component load-cell (Nissho LMC-3502) whose rated load is ±5kg and nonlinearity is within ±0.5%.

Flow visualization tests were performed in a circulating water channel with a test section of 300 x 250 mm^2 using particles tracing method. Poly-vinyl-chloride particles with an average diameter of 200μm were used as tracer particles. The particles were illuminated by a thin cold light-sheet supplied from a 150W halogen lamp. In this work, two-dimensional flow fields of the wake behind the nodal, saddle and middle planes were visualized. In addition, the turbulence structures of near wake were also investigated. The light sheet illuminated the wake centerline and flow visualization tests were carried out at Re = 3000, Re = 10,000.

3. Experimental results and discussion

3.1 Quantitative analyze

Total drag coefficients of two sinusoidal cylinder (λ/D = 1, 2 and one circular cylinder were shown in Fig 2. The maximum drag reduction of about 22% was archived (λ/D = 1) at Re = 10^4.

Fig. 3 shows the mean stream wise velocity profiles at X/D = 4, 6 and 8 for the case of U_0 = 4 m/s (Re = 5333). Flow direction is from left to right. The mean velocity profiles show a larger velocity deficit in the saddle plane than in nodal plane. With further increase of x/d, the velocity difference is decreased. These mean that the velocity recovery in the saddle plane is faster than that in nodal plane. Considering the larger reverse flow speed in the saddle plane, it is reasonable to conjecture that vortex shedding in the saddle plane entrains large amount of inviscid fluid from the outer stream than that in the nodal plane, that is responsible for the higher velocity recovery.

The turbulence intensity distributions of streamwise velocity component measured along the wake centerline were shown in Fig 4. Measurements were preformed at two Reynolds numbers, Re = 5333 and Re = 21600. Along the spanwise direction it is interesting thing to recognize the peak of streamwise turbulence intensity shifted down stream. In addition, the magnitude of the turbulence intensity decrease with the increase of Re. In this study, the end of vortex formation region was defined as location of the peak in the streamwise turbulence intensity distribution. The lengths of the formation region are summarized in the Table 1.

Compare with smooth cylinder, the vortex formation length of the wake behind sinusoidal cylinder is elongated. The model 2 (λ/D = 1) has larger value than the model 1 (λ/D = 2). Along the span of wavy cylinder, the formation region length show some variation. As point out by Bearman (1965), the formation length is inversely proposal to the base pressure coefficient C_{pb}. The drag coefficient C_D is due to pressure acting on the upstream and downstream side of cylinder. In the subcritical regime C_D is proportional to C_{pb}. The elongation of vortex formation region brings

Table 1. Noise level reduction of modified intake nozzles

Re	Circular cylinder	Wavy cylinder (Model 1)			Wavy cylinder (Model 2)		
		y = 0 mm	y = 10 mm	y = 20 mm	y = 0 mm	y = 5 mm	y = 20 mm
5333	2.2	2.85	3	3.2	2	2.2	2.3
21600	1.2	1.2	1.35	1.5	1.35	1.35	1.4

high pressure nearer to the rear side of the cylinder, hence the drag coefficient decreased. In addition, the extending of the vortex formation region move a way the vortices shed from the cylinder. The alternate shedding of vortices induces pressure fluctuations on the opposite side of the cylinder and results in a fluctuating C_L. It is reasonable to conclude that the long vortex formation length found in the wake of wavy cylinder would be consequent in drag reduction and the suppressing of vibration.

3.2 Flow visualization

Two-dimensional flow images of wake at nodal and saddle using a particle tracing method and the results are given in Fig 5 at Re = 3000 and Re = 10,000. This results show that the development of shear layer behind the geometric saddle resembles the smooth cylinder case. In the nodal plane, the wake is narrower and the rolling up of the separated boundary layer into streamwise vortices seem to suppress or delay the development vortices in the shear-layer.

Fig 6 shows the side views of the wakes behind two cylinders (λ /D = 1 and 2 wavy cylinder) at Re = 3000 and Re = 10,000. At Re = 3000, a low-energy fluid region exists between the trailing edge of cylinder and the vortices shed from the cylinder. The size of this region is decreased as Re increases. This shows a good agreement with the results obtained by hot-wire measurements. In addition, the streamwise vortices (termed ribs after Hussain) also can be figured out. For the sinusoidal cylinder of λ/D = 2, the presence of streamwise vortex is more clearly seen compared with the other wavy model of λ/D = 1 and smooth cylinder. In order to determine the influence of geometric on the streamwise vortex formation and near wake turbulent structure, more experiment on the separation mechanism on the boundary layer is needed.

4. Conclusion

Three-dimensional flow structures of wake behind sinusoidal cylinders were investigated experimentally. The vortex formation length of wavy cylinders is longer than the circular cylinder. The elongation of formation region length leads to reduction of drag and lift fluctuations. From flow visualization results, we can figure out the spanwise variation of streamwise vortices.

Acknowledgements

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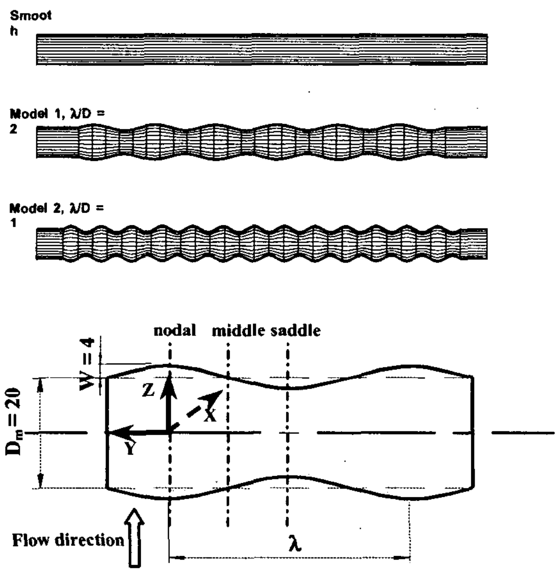

Fig 1. Geometric and terminology of sinusoidal cylinder

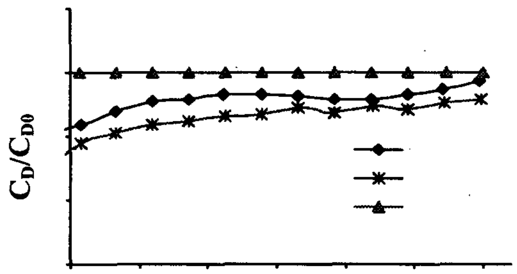

Fig 2. Total drag coefficients

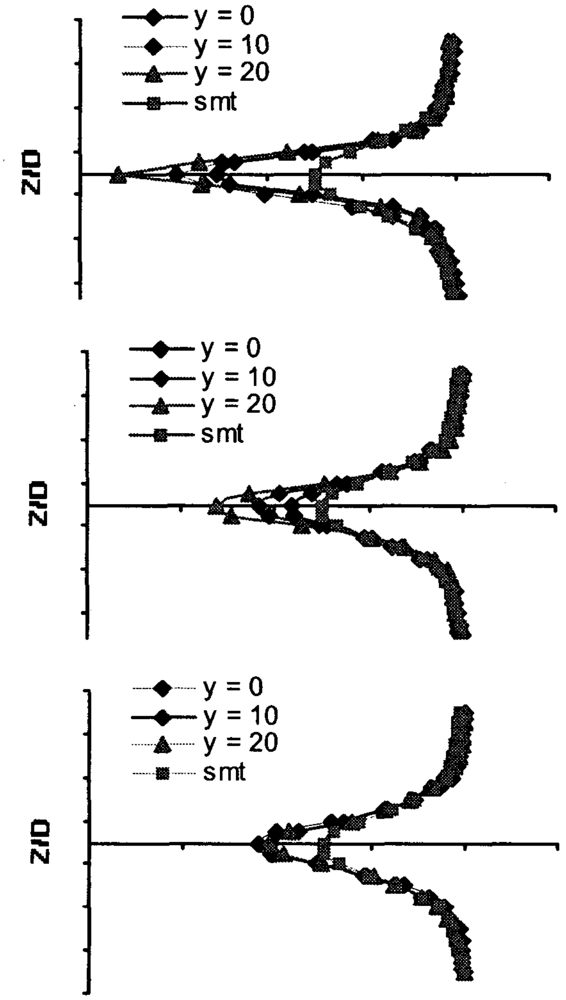

Fig 3. Variation of streamwise mean velocity profiles

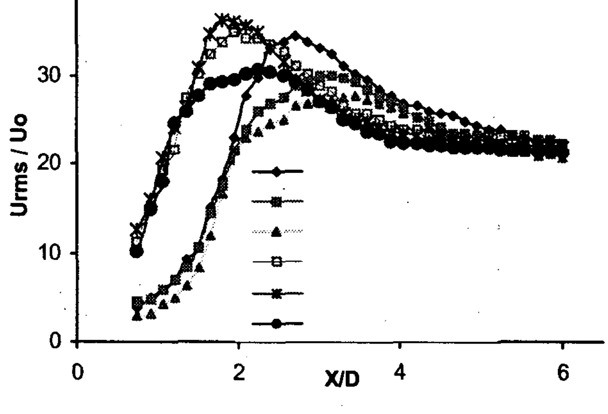

Fig 4. Stream wise turbulence intensity distributions

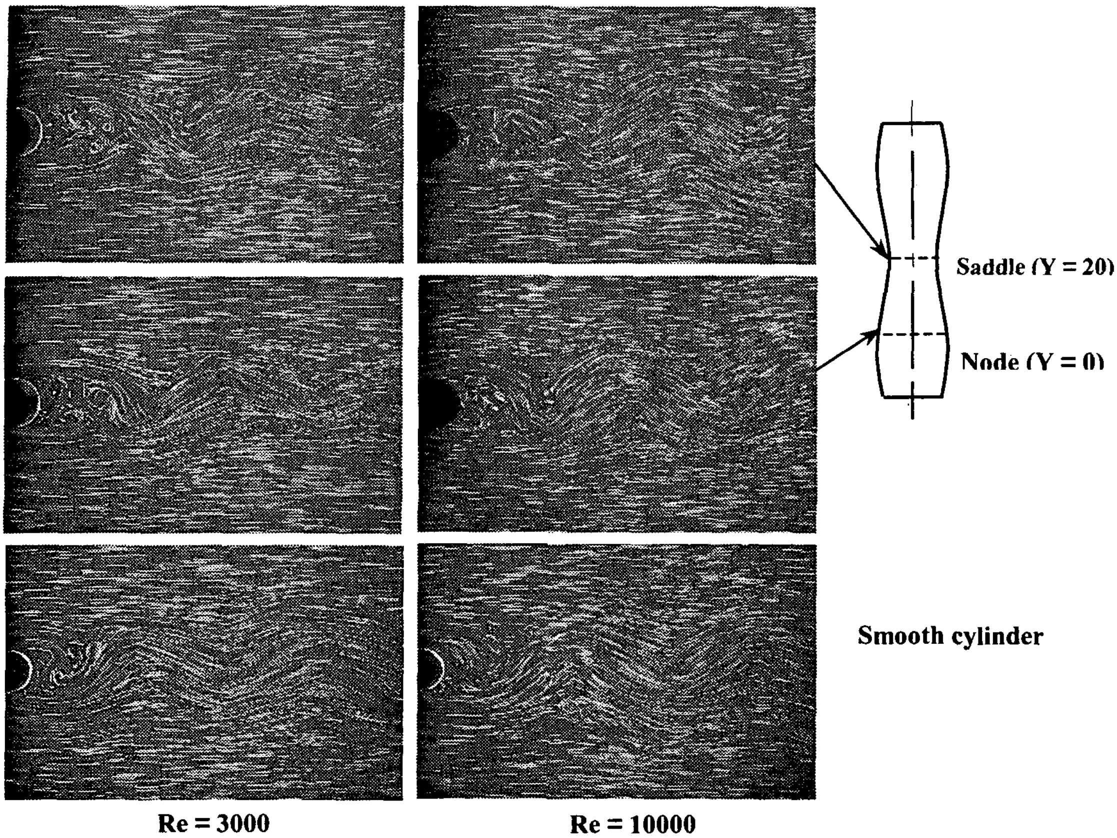

Fig 5. Visualized flow behind sinusoidal cylinder of λ/D = 2 in vertical cross-sections

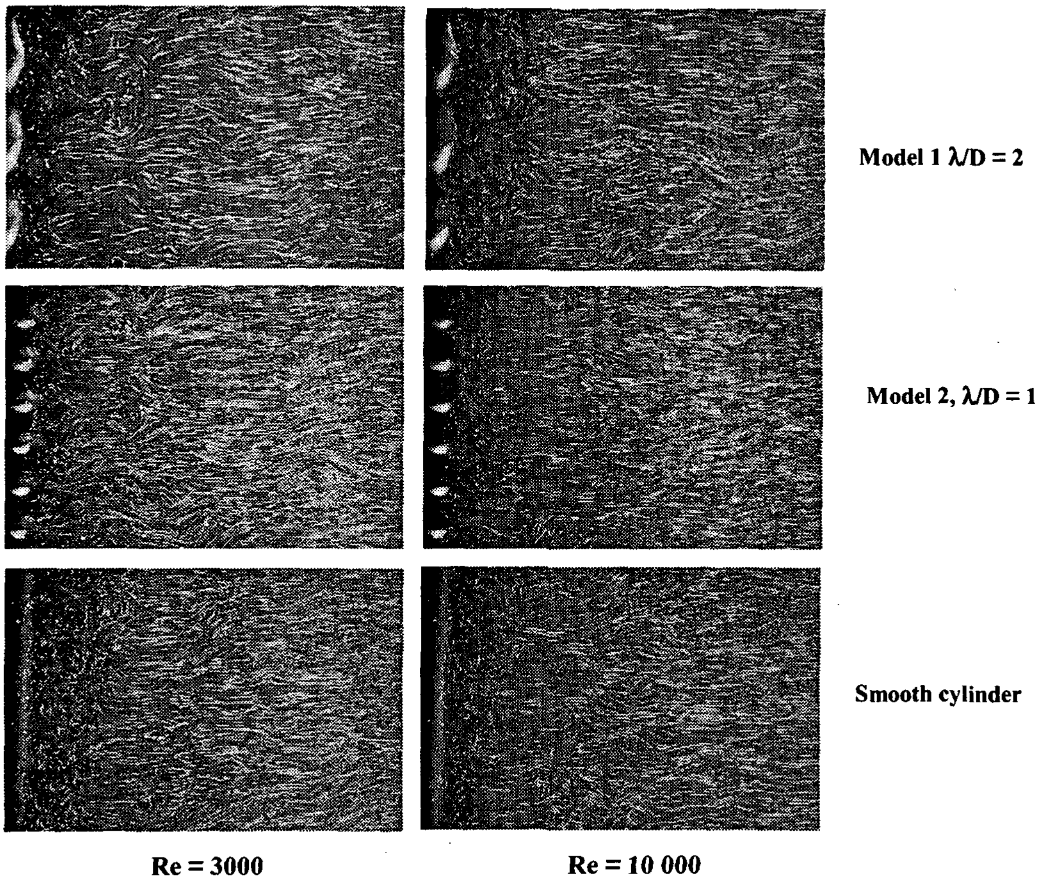

Fig 6. Side view of the wake behind sinusoidal cylinders (λ/D = 1 and 2)