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Flow characteristics of the two tandem wavy cylinders and drag reduction phenomenon*

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Abstract: This paper presents an extensive numerical study of 3-D laminar flow around two wavy cylinders in the tandem arrangement for spacing ratios (L/D_m) ranging from 1.5 to 5.5 at a low Reynolds number of 100. The investigation focuses on the effects of spacing ratio (L/D_m) and wavy surface on the 3-D near wake flow patterns, the force and pressure coefficients and the vortex shedding frequency for the two tandem wavy cylinders. Flows around the two tandem circular cylinders are also obtained for comparison. With the spacing ratio in the range of $L/D_m = 1.5 - 5.5$, unlike two tandem circular cylinders, the wavy cylinders in the tandem arrangement do not have the wake interference behaviour of three basic types. The vortex shedding behind the upstream wavy cylinder occurs at a further downstream position as compared with that of the upstream circular cylinder. This leads to the weakening of the effect of the vibration of the cylinders as well as a distinct drag reduction. The effects of the drag reduction and the control of the vibration of the two wavy cylinders in tandem become more and more evident when $L/D_m \geq 4.0$, with a distinct vortex shedding in the upstream cylinder regime for the two circular cylinders in tandem.

Key words: wavy cylinders, tandem arrangement, spacing ratio, drag reduction, vibration

Introduction

Flows past multiple cylindrical bodies are important in many engineering applications, for example, in the designs of cables, offshore structures, heat exchangers, high-rise buildings, and chimneys. The periodic vortex shedding and the fluctuating velocity fields behind the cylindrical bodies can cause structural damages, shorten the life of the structures and even lead to severe accidents. Hence, it is necessary to study the complicated flow around such multiple cylinders in order to improve the design of such equipment. The flow past cylindrical bodies, especially, that around one or two cylinders, has been extensively investigated. Williamson[1] and Wang[2] investigated the vortex dynamics of the wake behind a cylinder. For two circular cylinders in tandem arrangements, Lin et al.[3] and Deng et al.[4] investigated the near wake flow past two tandem circular cylinders and Jiang and Lin[5] studied the flows past two tandem cylinders of different diameters. These studies show that the flow around two tandem circular cylinders is sensitive to both Re and the spacing ratio (L/D). Zdravkovich[6] subdivided the flow patterns into three basic types based on the wake interference behaviour, Xu and Zhou[7] and Zhou and Yiu[8] also found the similar phenomenon, and a similar classification scheme was used by Carmo et al.[9,10], based on numerical simulations of two tandem circular cylinders. Sumner[11] reviewed the characteristics of two circular cylinders of equal diameter in a steady cross-flow.

It is a challenge to control the vortex-shedding phenomenon and hence to reduce the potential of flow-induced vibrations for the two cylinders in tandem arrangements. In order to suppress the associated bodies' vibration, many experimental and numerical investigations were carried out over the past years. In recent few years, several types of cylinders

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with a surface profile in sinusoidal curve along their spanwise direction, named the wavy cylinders, were introduced. The wavy cylinders can achieve the purpose of drag reduction and vibration damping at the same time. Lam et al.[12-15] investigated the control of force and bodies' vibration of a wavy cylinder. They identified the optimal value of the spanwise wavelength $(\lambda / D_m = 6)$ for the drag force reduction and the fluctuating lift suppression at $Re = 100$, and the maximum drag coefficient reduction can reach 18%, while the r.m.s. lift coefficient was equal to zero. Furthermore, they also found that a wavy cylinder with such a spanwise wavelength can provide a significant drag reduction and body vibration suppression for turbulent flows at subcritical Reynolds numbers from 6 800 to 13 400. Then they studied the three-dimensional flow characteristics of such optimal wavy cylinder with yaw angles from 0° to 60°. Lam et al.[16] investigated turbulent flows around two fixed unyawed and yawed out-of-phase wavy cylinders in tandem arrangement at a subcritical Reynolds number of 3 900.

With regard to the investigations on the cross-flow past two-tandem-cylinder arrays, most of the previous studies were focused on the effects of the spacing ratio on the two tandem circular cylinders. The effects of the spacing ratio of two-tandem-cylinder arrays and the wavy surfaces at the low Re have not yet been fully investigated. The understanding of the complex physical mechanism of 3-D flow characteristics around two wavy cylinders in the tandem configuration at low Re is still inadequate, as it is very difficult to gain this understanding by experimental measurements. The present investigation focuses on the effects of spacing ratio (L / D_m) and wavy surface on the 3-D instantaneous near wake flow patterns, force and pressure coefficients and vortex shedding frequency for the two tandem wavy cylinders of different spacing ratios at $Re = 100$. The main objectives of the present work are to discover whether this type of wavy cylinder configurations with various spacing ratios at low Re can still suppress bodies' vibration and reduce the drag force at the same time. In this paper, some valuable data, such as the drag, lift, the pressure, the velocity flied, the vortex shedding frequency and the flow pattern, are discussed in detail and compared with corresponding circular cylinders at the same arrangement. The physical mechanism of the drag reduction, as well as the influence of the upstream and downstream wavy cylinders will be studied. It is hoped that such an investigation will be helpful in engineering applications such as the vibrations of cables in suspension bridges and multiple risers in offshore engineering.

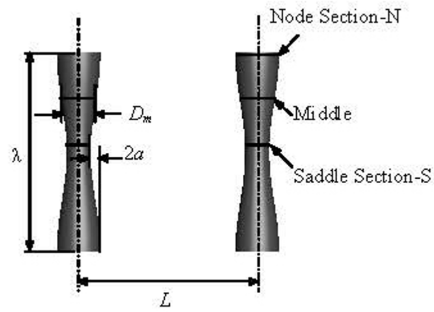

Fig.1 Geometric model of tandem wavy cylinders

1. Geometric of models

Figure 1 shows the geometric model of a wavy cylinder, the geometry of the wavy cylinders is described by the following equation

$$D_z = D_m + 2a \cos \frac{2\pi z}{\lambda} \tag{1}$$

where D_z denotes the local diameter of the wavy cylinder and varies in the spanwise direction z. The mean diameter D_m is defined by

$$D_m = \frac{D_{\min} + D_{\max}}{2}$$

The amplitude of the wavy surface a is equal to the half peak-to-peak distance. The axial location with the maximum local diameter $D_{\max}$ is called the "node", while the axial location of the minimum diameter $D_{\min}$ is called the "saddle". The "middle" is also defined at the midpoint position between the nodal and saddle planes. The diameter of the middle cross-section is equal to the mean diameter D_m. In the present study, all geometrical lengths are normalized with the mean diameter D_m. Furthermore, a circular cylinder with diameter D_m is used for the comparison study.

The flow past a wavy cylinder with $\lambda / D_m = 6$ and $a / D_m = 0.15$ over a wide range of Reynolds numbers was investigated by Lam and Lin[12] and Lam et al.[13,14]. The results of their investigations show that the vortex shedding behind a wavy cylinder is greatly suppressed and the drag force is significantly reduced at such a spanwise wavelength ratio and wave amplitude ratio. Therefore, the wavy cylinders in a tandem arrangement with a spanwise wavelength ratio of $\lambda / D_m = 6$ and a wave amplitude ratio of $a / D_m = 0.15$ are considered in the present study.