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In-line Dynamic Characteristic of a Circular Cylinder under Vortex-induced Vibration

XU Wan-hai[1], *WU Ying-xiang*[2], *HU Song-tao*[3], *DU Jie*[1]

(1. State Key Laboratory of Hydraulic Engineering Simulation and Safety, School of Civil Engineering, Tianjin University, Tianjin 300072, China; 2. Key Laboratory for Hydrodynamics and Ocean Engineering, Institute of Mechanics, Chinese Academy of Science, Beijing 100190, China; 3. XinXing Heavy Industries Group Co., Ltd., Beijing 100070, China)

Abstract: The in-line Vortex-induced Vibration (VIV) characteristics of a circular cylinder are investigated. A wake oscillator model is used for the in-line dynamic response prediction in the second excitation region. The near wake dynamics related with the fluctuating nature of vortex shedding is modeled based on the van der Pol equation. The influences of mass-damping parameter, mass ratio and structural damping factor on cylinder in-line VIV are discussed.

Key words: in-line vortex-induced vibration; circular cylinder; wake oscillator model; mass-damping parameter

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1 Introduction

Oscillation of cylinders in the in-line or cross-flow direction relative to an incident flow is a common occurrence in industry. Understanding these phenomena is of great importance in the design of a variety of offshore engineering structures, such as pipelines, cables and risers. Vortex induced vibration of cylinder structures has been the subject of extensive research for several decades. Sarpkaya[1], Gabbai and Benaroya[2], Williamson and Govardhan[3] had reviewed the studies on VIV. Recent experimental and theoretical works were summarized in these review articles.

The response in the in-line (or streamwise) direction has often been neglected in earlier VIV researches, mainly because cross-flow response amplitudes are larger. However, studies have shown that for free spanning pipelines and risers fatigue damage due to in-line response may become significant and even more critical than cross-flow[4]. Few studies were reported concerning with in-line VIV. Flow-induced streamwise vibrations of various kinds of cylindrical and axisymmetric bodies were reviewed in depth by Naudascher[5]. Two different modes

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Biography：XU Wan-hai(1981-), male, Ph.D. lecturer, E-mail: wanhaixu@hotmail.com;
WU Ying-xiang(1956-), male, researcher/tutor of Institute of Mechanics, Chinese Academy of Science.

of excitation occur within the in–line VIV, the first excitation region originates from symmetric vortex shedding in the lower reduced velocity region of $1.0<V_r<2.3–2.5$, while the second excitation region from alternate vortex shedding in the higher reduced velocity region of $2.3–2.5<V_r<3.8$ (V_r is the reduced velocity defined by $V_r=U/(f_nD)$), where U is the incident flow velocity, f_n is the natural frequency of a cylinder, and D is the cylinder diameter)[6–7]. Flow–induced in–line oscillation of a two–dimensional circular cylinder model was experimentally investigated in a wind tunnel using the free–oscillation method in order to understand some of the fundamental characteristics of the system by Matsuda et al[8]. Okajima et al[9] conducted on free oscillation tests in the steamwise direction for the circular cylinder elastically supported at both ends and a cantilevered model with aspect ratios from 5 to 21 in a water tunnel, instead of a wind tunnel, and the value of the mass ratio μ ($=m/\rho D^2$; m is a mass per unit span length, ρ is fluid density) is small. The mass–damping parameter C_n ($=2\mu\xi$; ξ is the structural damping factor) was varied over a wide range in order to evaluate the critical value at which the in–line oscillation is suppressed.

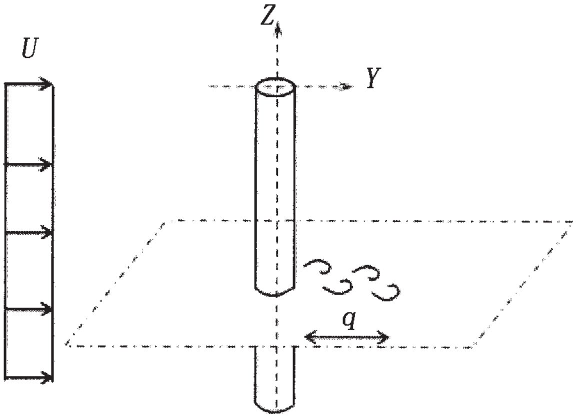

Fig.1 Model of coupled cylinder structure and wake oscillator for in–line vortex–induced vibration

Only a few analytical models have been proposed for the streamwise oscillation of structures. Currie and Turnbull[10] developed a wake–oscillator model, which attempts to represent a cylinder vibrating in the in–line direction, they thought that the cylinder oscillations in the second instability region were a simple harmonic of the velocity driven transverse cylinder oscillations, while those in the first instability region might be amplitude driven. An acceleration coupling wake oscillator model for the in–line oscillations in second synchronization region has been presented by Xu et al[11], some results showed the applicability and usefulness of the model for predicting in–line vortex induced vibration of engineering structures. Even fewer analytical models consider the possible coupling of the cross–flow and in–line responses as reported in several literatures. Kim and Perkins[12] adopted a similar approach in adapting the mathematic model in Balasubramanian and Skop[13] for drag, the principal mechanisms of coupled in–line and cross–flow motions of cable suspensions were identified during VIV. A time domain model has been formulated to examine flow induced vibration of cylindrical structures such as risers and free span pipelines by Furnes and Sorensen[14], the in–line and cross–flow deflections are coupled, the wake dynamics was described by the classical van der Pol equation. The dynamics of long slender cylinders undergoing vortex–induced vibrations was studied by Ge et al[15], the wake dynamics, including in–line and cross–flow vibrations, was represented using a pair of non–linear oscillators distributed along the cylinder.

For practical reasons, one cannot rely on numerical or experimental techniques for the long cylinder structures VIV prediction, rather one needs to rely on reduced-order models that take into consideration all of the physical aspects, are validated by a combination of numerical simulation and experiments, and are capable of reliably predicting and simulating VIV. The objective of this study is to investigate some aspect of the in-line VIV dynamics, which is hardly observed by experiments and numerical simulation. A simple wake oscillator model proposed by Xu et al[11] for the near wake dynamics of a cylinder in streamwise direction, was used to model the vortex shedding behind a structure.

2 Model description

A cylinder subjected to vortex-induced oscillations in the streamwise direction (Fig.1) is described as a damped mass-spring oscillator, the instantaneous drag in the second region is assumed to be associated with a vortex shedding frequency corresponding to two times the Strouhal number, and satisfies a van der Pol equation. Thus, the dimensionless structure and wake model can be written as[11]:

$$\ddot{y}+\left(2\xi\delta+\frac{\gamma}{\mu}\right)\dot{y}+\delta^2 y=s \tag{1}$$

$$\ddot{q}+\varepsilon\left(q^2-1\right)\dot{q}+4q=f \tag{2}$$

where the dot represents the derivative with respect to dimensionless time t, y is space coordinate in the in-line direction, $\delta=\Omega_s/\Omega_f$ is the reduced angular frequency of the structure, Ω_s is the structure angular frequency and the vortex shedding angular frequency $\Omega_f=2\pi StU/D$, where St is the Strouhal number, γ is a stall parameter, defined as $\gamma=\overline{C_D}/2\pi St$, $\overline{C_D}$ is the mean drag coefficient. The dimensionless wake variable q is associated to the fluctuating drag coefficient on the cylinder, it is defined as $q=2C_D/C_{D0}$, where C_{D0} could be interpreted as the fluctuating drag coefficient of a stationary cylinder, C_D is the instantaneous drag coefficient. s is the action of the fluid near wake on the structure, in dimensionless variables, and it can be expressed in the following form:

$$s=Mq,\quad M=\frac{C_{D0}}{16\pi^2 St^2\mu} \tag{3}$$

The action of the structure on the fluid wake $f=A\ddot{y}$, ε and A are the model empirical parameters.

In this paper, the fluctuating drag coefficient of a stationary cylinder C_{D0} is taken equal to 0.2[16]. Strouhal number St depends on Reynolds number, for the sake of simplicity, assuming $St=0.17$[17], the mean drag coefficient $\overline{C_D}=1.2$, the value of A as well as that of ε were determined from the experimental results on forced and free VIV, we had used a similar approach in the determination of wake oscillator model's empirical coefficients in streamwise VIV[11]. The parameter A can be expressed as:

$$A=12 \text{ for } 0\leqslant\omega\leqslant 2,\ A=8 \text{ for } \omega>2 \tag{4}$$

where ω is angular frequency, define as $\omega=1/(V_r St)$. We assumed that the maximum structure displacement amplitude was the same as the experimental results presented by $y_{2nd\_max}=0.172e^{-0.949C_n}$, the specification of the empirical parameter ε was given. The readers are referred to Ref.[11] for details of the calibration of model parameters.

3 Results and discussion

The reduced velocity V_r used in present calculation was varied from 2.3 to 3.8, which was defined as the second in-line VIV region. The influences of mass-damping parameter, mass ratio and structural damping factor on cylinder in-line VIV were investigated.

The response amplitudes are sensitive to the mass-damping parameter C_n in the second excitation region with alternate vortices; it is fundamental and important to evaluate the critical values of C_n for a two-dimensional cylinder like a heat exchanger and underwater riser, until now, there is almost no experiments observing the mechanisms of in-line VIV while C_n is much small. Fig.2 shows the response curves of in-line oscillation of a circular cylinder at three really small mass-damping parameters C_n=0.2, 0.4 and 0.6. Keeping the mass ratio μ=10.5[18], it can be seen that the response amplitude of the in-line oscillation damps with increasing C_n value in the second excitation regions. There is an increase in streamwise amplitude from V_r=2.3 to 2.9, and a decrease from V_r=3.1 to 4.0, with the maximum value obtained at V_r=3.0.

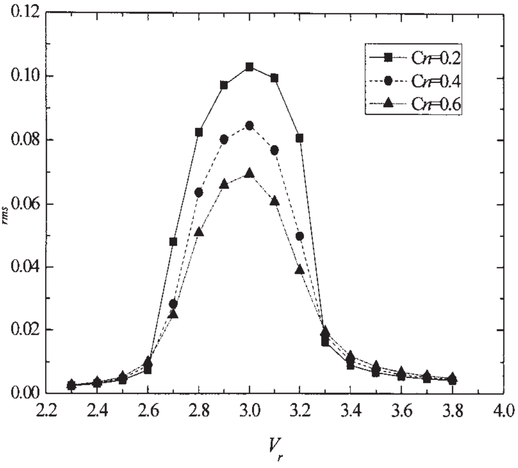

Fig.2 The response amplitude of a two-dimensional circular cylinder with different values of C_n

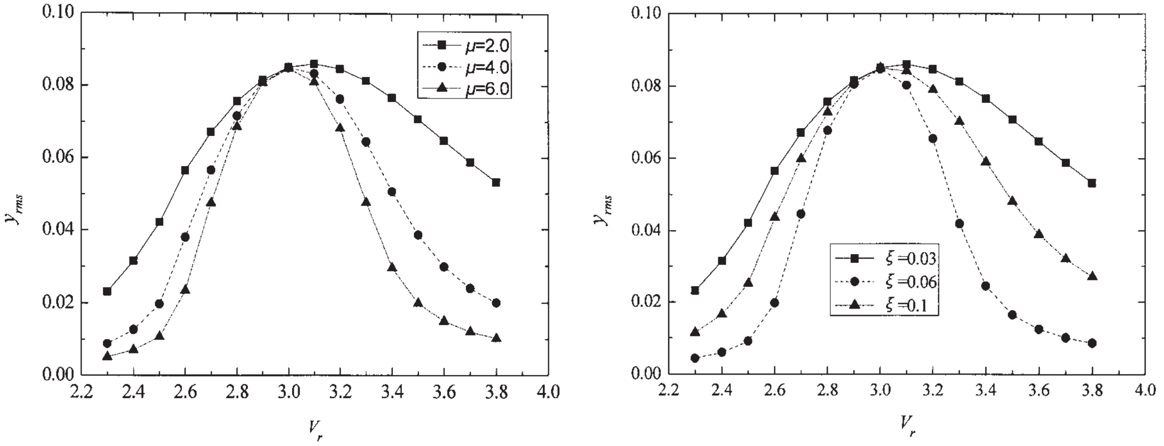

Fig.3 The response amplitude of a two-dimensional circular cylinder with different values of mass ratio μ

Fig.4 The response amplitude of a two-dimensional circular cylinder with different values of structural damping factor ξ

Although the maximum in-line structure displacement determined by the combined mass-damping parameters C_n, the range of lock-in is known to be a function of both, the mass ratio μ and structural damping factor ξ, separately. The lock-in domain is here considered at C_n=0.4, the response amplitude of in-line oscillation of a circular cylinder was calculated at three small mass ratio μ=2.0, 4.0 and 6.0. Cross-flow VIV experiments had shown the existence of a critical mass ratio makes lock-in domain unbound at higher reduced velocity, while there is no experiments concerned the in-line VIV characters of a circular cylinder at really small mass ratio μ; this is the reason why we investigate the mass ratio μ influence on the in-line VIV, here. It can be seen that the maximum response amplitude nearly remains the same while mass ratio is different in Fig.3. It is noted that the phenomenon of persistent lock-in remained at μ=2 and a critical mass ratio may exist. This conclusion should be further confirmed by extra in-line VIV experiments.

At low values of the mass-damping parameter, C_n=0.4, the in-line VIV dynamical behavior of a cylinder is discussed. The root mean square vibration amplitude is presented in Fig.4 for the ξ=0.03, 0.06 and 0.1 cases. It can be found that the response amplitude reaches maximum value while reduced velocity V_r is nearly at the same value 3.0.

4 Conclusions

In this paper, some aspect of the streamwise vortex-induced vibration characteristics of a circular cylinder, which is hardly observed by experiments, was investigated. A wake oscillator model, which has been proved the applicability and usefulness for predicting in-line VIV of engineering structures, was used. It can be found that the response amplitudes are sensitive to mass ratio and structural damping factor. There is a critical mass ratio, just like the cross-flow VIV of a cylinder. This needs confirming in further in-line VIV experiments.

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刚性圆柱结构顺流向涡激振动特性分析

徐万海[1]，**吴应湘**[2]，**胡松涛**[3]，**杜 杰**[1]

（1. 天津大学 水利工程仿真与安全国家重点实验室，天津 300072；2. 中国科学院力学研究所水动力学与海洋工程重点实验室，北京 100190；3. 新兴重工集团有限公司，北京 100070）

摘要：文章研究了刚性支承圆柱的顺流向涡激振动特性，在第二激励区域，运用 van der Pol 方程描述漩涡脱落的尾迹特性，采用尾流振子模型计算圆柱结构的响应，讨论和分析了质量-阻尼参数、质量率和结构阻尼对顺流向涡激振动的影响机理。

关键词：顺流向涡激振动；圆柱；尾流振子模型；质量-阻尼参数

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作者简介：徐万海（1981-），男，天津大学建筑工程学院讲师；研究方向为船舶与海洋结构物的动力学特性，结构疲劳破坏分析等；

吴应湘（1956-），男，中国科学院力学研究所研究员，博士生导师；

胡松涛（1980-），男，新兴重工集团有限公司工程师；

杜 杰（1961-），男，天津大学建筑工程学院副教授。