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Dynamic characteristics of an inclined flexible cylinder undergoing vortex-induced vibrations

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ABSTRACT

A series of experimental tests were conducted on vortex-induced vibrations (VIV) of a flexible inclined cylinder with a yaw angle equals 45° for investigating the response characteristics in a towing tank. The flexible cylinder model was 5.6 m in length and 16 mm in diameter with an aspect ratio of 350 and a mass ratio of 1.9. The Reynolds numbers ranged from about 800 to 16,000.The strain responses were measured directly in both cross-flow (CF) and in-line (IL) directions and corresponding displacements were obtained using a modal approach. The dynamic response characteristics of the inclined flexible cylinder excited by vortex shedding was examined from the aspect of strain response, displacement amplitudes, dominant modes, response frequencies and drag force coefficients. The experimental results indicated that the CF response amplitude could be up to a value of 3.0*D* and the IL one more than 1.1*D*. The dominant modes were from 1 to 3 in CF direction and 1 to 5 in IL direction. And it was found that dominant frequencies increased linearly with the reduced velocity. The multi-modal response of the flexible inclined cylinder model excited by VIV was observed and analyzed. Moreover, the values of drag coefficients were in the range of 0.9–2.6.

1. Introduction

Vortex-induced vibrations (VIV) easily occur in many engineering situations, such as chimneys, cables of stay bridges, free spanning pipelines, marine risers, tendons in Tension Leg Platform and other structures with circular cross-sections. VIV is a crucial source of fatigue damage for long cylindrical structures that are exposed to air or water flow. Therefore, this complicated flow-structure interaction phenomenon has been investigated by a large number of researchers over the past decades. More details can be found in recent comprehensive review papers [1–4]. However, most of these reviews are focused on the VIV of elastically mounted rigid cylinders where the flow velocity direction is perpendicular to the cylinder axis.

In practical engineering applications, the cylinders are often inclined with respect to the direction of the oncoming flow. To simplify the VIV model of inclined cylinders, a hypothesis named Independence Principle (IP), was supposed. It assumes a cylinder behaves similarly in both the inclined and normal-incidence cases, if the normal component of the free flow

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velocity to the cylinder axis is the only consideration. Effects of the axial component can be ignored accordingly. Previous researchers have conducted some laboratory investigations and numerical simulations for validating the IP hypothesis and investigating the response characteristics of inclined cylinders. Lucor and Karniadakis [5] employed direct numerical simulation (DNS) to investigate the validity of the IP for fixed yawed circular cylinders and free yawed circular rigid cylinders subject to VIV at subcritical Reynolds number. Two large yaw angles (60° and 70°) in relation to the direction perpendicular to the oncoming flow direction were analyzed. They pointed out that the IP was not applicable to fixed yawed cylinders with large angles of inclination and CF-VIV amplitudes of freely moving cylinders decreased for increasing angles of yaw at lock-in. Franzini et al. [6] performed some measurements on VIVs of inclined cylinders in a Reynolds number range between 2000 and 8000. They observed that the oscillation amplitudes of the inclined circular cylinder were just slightly lower than those observed in experiments for the vertical cylinder, and the fluid forces showed similar behaviors. These findings supported the reasonability of the IP with yaw angle up to 45°. Franzini et al. [7] further experimentally studied the flow characteristics and the dynamic response of cylinders subjected to oblique flow at a re-circulating water channel. Five yaw angles (0°, 10°, 20°, 30° and 45°), both in the upstream and downstream orientations, were investigated. Obvious differences were observed between the upstream and downstream results. Recently, In order to testify the validity of the IP hypothesis for the vibration amplitude and frequency without the influence from the end effects, Zhao [8] used the finite element method and periodic boundary condition to simulate the VIV of an inclined cylinder with the yaw angle 45° in steady flow. It was found that the response amplitude and frequency for a yaw angle of $a=45^\circ$ agreed well with their counterparts for $a=0^\circ$, and validated the IP applicably for the response amplitude and frequency. However, the VIV characteristics of inclined rigid cylinders have not been fully understood so far.

In contrary to the large number of published papers dedicated to the VIV problem of inclined rigid cylinders, the problem of inclined flexible cylinders undergoing VIV has not yet attracted much attention. Only a few literatures are available on this subject. King [9] investigated the VIV of inclined flexible circular cylinders in the subcritical Re range of 2000–20,000 and for yaw angles ranging from $-45°$ to $+45°$. It was pointed out that the response of the cylinder was the same for both negative and positive angles and the maximum amplitude increased with an increase in inclination. These findings were conflicting with the experimental results of yawed rigid cylinders by Franzini et al. [7]. Bourguet et al. [10] numerically studied the VIV of an inclined flexible cylinder with the yaw angle 60° by DNS. The Reynolds number and aspect ratio in their simulation were equal to 500 and 50 respectively. Two values of the non-dimensional tension defined by $T/\rho U^2 D^2$ (where T is axial tension, ρ is the flow density, U is the velocity of oncoming flow, D is the diameter of cylinder) were adopted. They found that the inclined cylinder exhibited regular VIV in both IL and CF directions, and the IP hypothesis was valid in the high-tension configuration but was not reasonable in the low- tension configuration. Bourguet and Triantafyllou [11] investigated the free vibrations of a flexible circular cylinder inclined at a much larger angle, 80°, than those in their previous research work [10] within a uniform flow. The vibrations and fluid forces in the inclined case were compared with those of normal body configurations. They observed that the behavior of inclined flexible cylinder at the yaw angle 80° generally departed from the IP. Recently, experiments on the VIV of a curved flexible cylinder free to oscillate in the CF direction was performed in the convex and the concave orientations [12]. The cylinder had a 10 mm diameter and a 470 mm radius of curvature. It was observed that the oscillation amplitude in each configuration was decreased compared to a vertical cylinder with the same mass ratio.

In offshore activities, the marine cylinder structures, e.g. risers and cables generally have high aspect ratio (length to diameter) and small mass ratio (structural mass to displaced fluid mass). When flow is perpendicular to a flexible cylinder structure axis and passes across the cylinder, some more complicated phenomena may appear, e.g. multi-mode vibration, higher harmonic responses and traveling wave dominant response [13–25]. To the best of authors' knowledge, the dynamic response characteristics of the inclined flexible cylinders at larger yaw angle are very sophisticated and still unknown. The main purpose of this paper is to investigate the VIV characteristics of an inclined flexible cylinder with a yaw angle 45°. The laboratory tests were carried out in a towing tank. The uniform flow was generated by towing the cylinder model with an aspect ratio 350 and a mass ratio 1.9.

This paper is organized into the following sections. In Section 2, the experimental set-up is presented. Section 3 introduces the modal approach for analyzing experimental data. Section 4 contains the test results and the investigation of dynamic characteristics of the inclined flexible cylinder. Finally, some conclusions are drawn in Section 5.

2. Experimental description

A series of laboratory tests have been conducted in the towing tank at the State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University. The towing tank is 137.0 m long, 7.0 m wide and 3.3 m deep. An experimental apparatus, which is shown in Fig. 1, was designed and used in the tests. This apparatus was mounted inclined to the carriage moving direction. The yaw angle, $a=45°$ in relation to the direction perpendicular to the carriage moving route was selected in our experiments.

This apparatus consisted of a supporting structure, two vertical supporting mechanisms, a cylinder model and an axial tension system. Several steel beams were tightly welded together to constitute the supporting frame. And there were mainly four parts in each vertical supporting mechanism, including an angle plate, a vertical supporting rod, a supporting plate and a guide plate. Several angle standard lines were drawn on the angle plate, more details can be found in Fig. 2a. The guide