Experimental Study on the Vortex-induced Vibration of a Catenary Flexible Riser under Sheared Flows

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The vortex-induced vibration (VIV) of a catenary flexible riser subjected to log-law sheared flows is experimentally investigated in a Reynolds number range of 308–953. The in-plane and out-of-plane responses are captured using the nonintrusive imaging technique. Experimental results illustrate that the mode transition is out of sync in the in-plane and out-of-plane directions, though the excited mode increases with the reduced velocity. Furthermore, the spatial variation of dominant frequency suggests the out-of-sync mode transition along the span. The predominant out-of-plane frequency is also observed in the in-plane response, whereas the in-plane dominant frequency differs when the reduced velocity is sufficiently large.

INTRODUCTION

The dynamic response of a circular cylinder exposed to flows is widely encountered in engineering applications. In particular, in offshore oil and gas engineering, the elongated flexible riser as a result of the increasing water depth experiences more complicated vortex-induced vibration (VIV) with the presence of multiple frequencies and mode competition. The vigorous VIV response is the main reason for structural fatigue damage: 15.8% of the submarine pipeline failures that occurred in the Gulf of Mexico during 1967–2012 were caused by VIV, as statistically reported by the Bureau of Safety and Environmental Enforcement (BSEE). These pipeline fatigue damages resulted in huge economic loss and serious environmental pollution (Marshall, 2021). Thus, a comprehensive understanding of the VIV response of flexible cylinders with a large aspect ratio is urgently required to predict and prevent fatigue failure (Wang et al., 2019). VIVs of flexible cylinders in uniform flows have been extensively investigated in past decades. The considered flexible cylinder in the experiments conducted by Song et al. (2011) has a large aspect ratio of 1,750. Although the cylinder is subject to uniform flow, asymmetric response was observed, with the highest mode reaching the sixth in the cross-flow direction. Whitney et al. (1981) pointed out that higher modes can be excited even at low towing speeds for very long marine pipes of aspect ratios 1,800, 5,400, and 10,800 with a bottom end mass. Sun et al. (2012) reported that the excited mode increased with the incident current velocity.

As a result of the monofrequency response, a standing wave pattern was observed by Zhang et al. (2013) in their experimental study on the VIV of a straight flexible cylinder in uniform current. A travelling wave component emerges in the presence of multiple frequencies, as reported in Fan et al. (2019) and Feng et al. (2019). To meet the nonlinear velocity profile characteristics of currents, Srinil (2011) numerically investigated the dynamic behavior of a variable-tension riser in linearly sheared currents. An asymmetric response with mode switching over time was observed. An experimental study conducted by Gao et al. (2015) illustrated the multimode characteristics of a straight flexible pipe in linearly sheared flows. Because the submarine risers are usually deployed in catenary configuration, Assi et al. (2012) experimentally investigated the VIV of a rigid-curved cylinder in both concave and convex configurations in uniform flows. The distinguishing feature was found in the curved cylinder as opposed to a straight one. The cylinder in concave configuration exhibited a relatively high amplitude that persisted beyond the typical synchronization region.

The extant literature involving the catenary flexible cylinder subject to nonlinear flows is scanty. Therefore, the VIV of a catenary flexible pipe with an aspect ratio of 158 under log-law sheared flows is experimentally investigated in the present work. The aim of this study is to improve the understanding of the spatial-temporal dynamic behavior of a curved flexible cylinder in nonlinear flows and the associated mode transition.

EXPERIMENTAL SETUP

A series of experiments was conducted in a recirculating water flume in the Offshore Oil and Gas Laboratory of Southwest Petroleum University. The water flume is composed of three glass walls on the horizontal bottom and two vertical sides, leaving the top open, and it has a test section of 1,000 mm height × 500 mm width × 2,000 mm length. In the tests, the water depth was set as 0.6 m, and stable sheared flows with mean velocities ranging from 0.01 m/s to 0.8 m/s are achieved at this water depth via arranging a cuboid frame filled with steel wire balls in the upstream of the test section, simultaneously stabilizing the incoming flow.

The schematic of the experimental setup is depicted in Fig. 1. The riser base is normally connected to submarine pipelines or a manifold that is mounted on a high-stiffness seabed. As reported in Hobbs (1986), the fixed support is a typical end condition for such pipelines, confirmed by Anfinsen (1995) and Fyrileiv and Mørk (2002). For a riser with a top connected to a moving tower subjected to wind and currents, the top boundary condition could be conservatively assumed to be fixed as a clamp arrangement (Babin et al., 1999). Additionally, the fixed support is usually employed as a simplified boundary condition for risers in experimental investigations, as reported in Dalheim (1999), Domala.