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Distribution of drag force coefficient along a flexible riser undergoing VIV in sheared flow

Leijian Song [a,b], Shixiao Fu [a,b,c,*], Siyu Dai [a], Mengmeng Zhang [a,b], Yifan Chen [d]

[a] State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, Shanghai, China
[b] Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration, Shanghai 200240, China
[c] Marintek, Trondheim, Norway
[d] Mechanical Engineering School of Engineering, University of Kansas, 1450 Jayhawk Blvd, Lawrence, KS 66045, USA

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ABSTRACT

The drag force coefficients of a flexible riser undergoing vortex-induced vibration (VIV) in sheared flow are investigated for Reynolds numbers (Re) up to 1.2×10^5. Based on the drag forces theoretically calculated by the beam theory using the strains measured in a scale model test, the properties and distribution of the drag coefficients are investigated, and a new empirical model for estimating the drag coefficient on a flexible riser undergoing VIV is proposed. The results show that VIV leads to non-uniform distribution of the drag coefficient and amplifies the drag coefficient, and the local drag coefficient can reach up to 3.2. For Re values from 1.0×10^4–1.2×10^5, the mean drag coefficient is between 1.3 and 2.0 and decreases as Re increases. Furthermore, the empirical drag coefficient prediction model obtained from experiments under low Re is not suitable for high Re. The corrected empirical prediction model, which accounts for the effect of the flow velocity, the VIV dominant mode number and the dominant frequency, can be used to predict riser drag coefficients under VIV more accurately at high Re values up to 1.2×10^5.

1. Introduction

The hydrodynamic forces acting on a flexible riser with a certain length and diameter in a flow field consist of the lift force in the cross flow (CF) direction and the drag force in the inline (IL) direction. The lift force exhibits periodic oscillations around a zero mean and causes the riser to vibrate with a high frequency and small amplitude, i.e., vortex-induced vibration (VIV) in the CF direction. The drag force can be divided into a periodic oscillating drag force and a mean drag force. The periodic oscillating drag force can result in VIV in the IL direction. For flexible risers, the VIV in CF and IL directions can lead to the rapid accumulation of fatigue damage. The mean drag force causes steady deformation of the riser with relatively large amplitude, which therefore affects the structural strength of the riser (Sumer and Fredsoe, 2006). The Morison equation is usually used to calculate the mean drag forces on risers in their strength and safety design, and a drag coefficient of 1.2 for a rigid cylinder towed in a tank is usually adopted in most specifications (API, 1998). However, studies have shown that VIV can not only disrupt the hydrodynamic force distribution along the riser but also significantly amplify the mean drag forces on flexible risers, resulting in a drag coefficient that is generally larger than 1.2 (Vandiver, 1983; De Wilde and Huijsmans, 2004; Chaplin et al., 2005; Zhao and Wang, 2010). Since hydrodynamics of risers subjected to VIV are not well understood so far, a factor of safety greater than 10 is normally used in the riser design to prevent failure (API, 1998). However, with the development of oil and gas resources into deeper waters, the structural integrity of risers cannot be insured simply by increasing the safety factor. Hence, investigations into the mean drag force on flexible risers undergoing VIV and the amplification of drag coefficient caused by VIV are becoming more necessary.

Due to the development of scientific computation, computational fluid dynamics (CFD) has become a very powerful and efficient tool. CFD is an ideal method with which to study complex fluid-structure interaction (FSI) problems such as VIV (Sarpkaya, 2004; Kaiktsis et al., 2007). In most CFD studies of a flexible cylinder's VIV, the structure is simplified as a tensioned-beam model and divided into a large number of rigid segments; while the flow along each segment is assumed to be two-dimensional or three-dimensional. The related FSI studies of a flexible cylinder have been extensively conducted to study the hydrodynamic

* Corresponding author at: State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, Shanghai, China.
E-mail addresses: shixiao.fu@sjtu.edu.cn, shixiao.fu@marintek.sintef.no (S. Fu).

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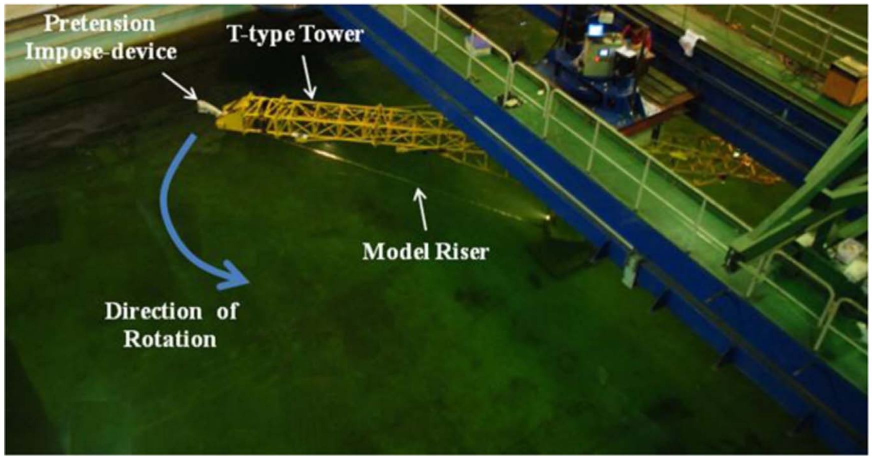

Fig. 1. Experimental setup for a flexible riser in a sheared flow.

characteristics and structural response of flexible risers (Evangelinos et al., 2000; Willden and Graham, 2001; Yamamoto et al., 2005; Zhao and Wang, 2010; Liu et al., 2012).

Scale-model test is another method to study the hydrodynamics of flexible risers undergoing VIV. However, in model testing, it is challenging to directly measure the drag force on a riser under a current; thus, researchers often measure the total drag force by mounting force sensors at the ends of the models (Baarholm et al., 2007; Fu et al., 2011, 2014; Fang et al., 2014; Wang et al., 2014). Moreover, Huera-Huarte et al. (2006) determined the fluid forces by using displacement measurements at various measuring points as the input to a finite element analysis of a vertically tensioned riser exposed to a stepped current. The authors found that the distribution of drag force along the riser model was the same as the distribution of the root mean square (RMS) of VIV displacement in the CF direction and the maximum local drag coefficient reached up to 4.5. Jhingran et al. (2008) described a simplified method to calculate the local drag on long risers in sheared flow using the strain signals measured in the field test. However, in this simplified method, the component of the drag force corresponding to the bending stiffness was ignored, and only the component corresponding to the tension was considered. The above analysis show that studies demonstrating methods to obtain the drag forces of flexible risers undergoing VIV in model testing are scarce and the characteristics of the mean drag force on flexible risers undergoing VIV still need further research.

Amplification of drag forces due to VIV has been studied for many years. Vandiver (1983) experimentally investigated the effect of VIV on the drag coefficient for a flexible riser and found that the drag coefficient depended nonlinearly on the RMS of VIV displacements in the CF direction. While, Blevins (1990) reported that the drag coefficient depended linearly on the RMS of CF VIV displacements. Using model tests, Chaplin et al. (2005) found that the mean drag coefficient was a quadratic function of the standard deviation of the flexible riser's CF VIV displacements in a stepped current. However, in the aforementioned studies, the largest Reynolds numbers (Re) investigated was only on the order of 10^4, whereas in practical situations, risers are subjected to Re values on the order of 10^5 or more. Since the flow characteristics and flow separation modes depend strongly on Re (Morse and Williamson, 2009), the performance of the drag force and VIV of risers under high Re may be different from those under low Re. Thus, further studies are required to determine whether the test results for Re below 10^4 are representative of the VIV amplification on the drag coefficient at higher Re.

In this study, the characteristics of the mean drag force on flexible risers undergoing VIV in linearly sheared flow and the VIV amplification on the drag coefficient were investigated by a scaled model test. Re values up to 1.2×10^5 were investigated. In tests, the strains on the surface of the riser model were measured. Based on the measured strains, the mean drag force at different cross sections of the riser model was calculated by beam-bending theory, and the drag coefficient distribution was investigated as a function of the Re. The test results were then used to formulate an empirical equation for estimating the drag coefficient of flexible risers undergoing VIV.

2. Experimental apparatus

In the experiments, the top and the bottom of the riser model were connected to the pretension-impose-device and the center shaft of a tower through universal joints, respectively, and maintained a constant pre-tension. The angle between the riser and water surface was 16°. The riser model was driven to rotate in the tank by the tower and the relative sheared flow was produced by controlling the rotation velocity of the tower. During the experiments, the flow velocity at the top of the riser model was the largest, and the velocity at the bottom was zero. A photograph of the experimental setup is shown in Fig. 1.

The outer diameter of the model riser was 0.03 m with an effective length of 6.75 m. To guarantee the smoothness on the surface of the riser model, a thin sleeve plastic tube with thickness of 0.5 mm was covered outside of the riser model. Thus the hydrodynamic diameter of the riser model is 0.031 m. The detailed parameters and the first four orders of natural frequencies in still water (with added-mass coefficient of 1.0) of the riser model are listed in Table 1.

In the experiments, the Fiber Bragg Grating (FBG) strain sensors were instrumented on the surface of the riser model in CF and IL directions to measure the strain responses. Four FBG strain sensors were placed on four points of the opposite sides of a cross section denoted as CF1, CF2, IL1 and IL2, as shown in Fig. 2, whose strains

Table 1
Parameters of the riser model.

Parameter	Value	Parameter	Value
Hydrodynamic diameter (m)	0.031	Inner diameter (m)	0.027
Mass per unit length (kg/m)	1.768	Bending stiffness (N m^2)	1476.763
Length/diameter ratio	225	Axial stiffness (N)	1.45×10^7
Mass ratio	2.5	Pretension (N)	2943
f_1 (Hz)	2.69	f_2 (Hz)	6.12
f_3 (Hz)	10.77	f_4 (Hz)	16.91