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Experimental investigation on the dynamic responses of a free-hanging water intake riser under vessel motion

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ABSTRACT

A large-scale model test of a free-hanging water intake riser (WIR) is performed in an ocean basin to investigate the riser responses under vessel motion. Top end of the WIR is forced to oscillate at given vessel motion trajectories. Fiber Brag Grating (FBG) strain sensors are used to measure the WIR dynamic responses. Experimental results firstly confirms that the free-hanging WIR would experience out-of-plane vortex-induced vibrations (VIVs) under pure vessel motion even for the case with a *KC* number as low as 5. Meanwhile, comparison between numerical results and experimental measurements suggests a significant drag amplification by out-of-plane vessel motion-induced VIV. What's more, further study on WIR response frequencies and cross section trajectories reveals a strong correlation between vessel motion-induced VIV and local *KC* number distribution, owing to the small *KC* number effect. The presented work provides useful references for gaining a better understanding on VIV induced by vessel motion, and for the development of future prediction models.

1. Introduction

As oil and natural gas exploration and production extend to increasingly deep waters, new offshore production concepts have been developed recently including the floating liquefied natural gas (FLNG) system [1]. To improve the FLNG process efficiency and also for the economical consideration, free-hanging water intake risers (WIRs) are proposed to pump up cold water from the sea bottom to the vessel deck for the cooling process and power systems. Ocean currents, vessel motion-induced riser global responses, high internal flow velocities and large diameter (up to several meters) are the major design issues for the WIRs.

When it comes to the ocean current, vortices will be generated in the wake of the riser. The alternate vortex shedding would lead the riser to oscillate in both cross-flow (CF) and in-line (IL) directions, which are called vortex-induced vibrations. VIV may lead to rapid accumulation of fatigue damage of the riser system, and amplify drag forces of the riser systems. These issues have been studied in depth over the last three decades [2–9].

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Vessel motion is the other external load for the riser systems. Currently, riser global responses under vessel motion can be numerically calculated by most of the riser analysis software like OrcaFlex [10], Riflex [11] and etc. The uncertainties of these numerical simulations are mostly caused by the insufficient understanding on the hydrodynamic loads [12], for example, drag amplification by VIV [13], and nonlinear problems like riser-soil interaction [14]. Luis [15] conducted a large scale field test on WIR connected to a barge, he reported the modal frequency dependent pipe added mass coefficients were in the range from 0.26 to 0.78. Recently, Halkyard [16] conducted a WIR model test in an ocean basin, which mainly focused on the riser global dynamic responses under vessel motion. However, other WIR responses, such as internal flow effect and vortex induced vibrations were not addressed.

Recent research also indicates that in addition to the ocean current-induced VIV and vessel motion induced riser global motion, vessel motion can also lead to significant out-of-plane VIV to the compliant risers [17–20]. This phenomenon occurs because the riser will be exposed to the oscillatory flow due to its relative motion with respect to the water particles around. According to the experimental investigations, vessel motion-induced VIV for the compliant risers is characterized with strong time-varying features, which is recognized as one of the major differences compared to VIV under ocean current [20]. Meanwhile, maximum *KC* number and maximum in-plane velocity are found to be the two dominant parameters governing vessel motion-induced VIV features when maximum *KC* number is large enough (larger than 40 typically [20]). As to the WIR, the *KC* number along the riser under vessel motion is much smaller thanks to its large diameter. However, considering its bottom boundary condition as a free end, the WIR could possibly have a considerable global in-plane motion along the entire riser. This brings up the question whether the WIR also experience vessel motion-induced VIV under a small *KC* number scenario? Besides, the internal flow further adds more uncertainty to this problem.

To evaluate the hydrodynamic performance of the WIR under vessel motion and considering the internal flow effect, a large scale model test was carried out for SBM Offshore in the ocean basin at Shanghai Jiao Tong University in November, 2013 [21,22]. The scopes of the model test were to measure the dynamic responses of the riser under vessel motion; to investigate the internal flow effect; to observe the occurrence of VIV and axial instability due to vessel motion and/or internal flow. The aim of the test cases reported in this paper is to preliminarily investigate the relationship between the vessel motion, WIR in-plane global motion and out-of-plane VIV responses.

2. WIR model test

2.1. Model test design

The prototype WIR has a large outer diameter at around 4 m with the water depth at around 1000 m. The Froude similarity is applied as the scaling law to obtain the geometry, weight and vessel motion (*KC* number) for the scaled model. The Cauchy similarity is applied as the scaling law to obtain the structural properties like axial stiffness and bending stiffness. Considering the maximum water depth of the test basin pit is 40 m, the WIR is designed to have a scaling factor at 26, and the corresponding designed physical properties at model scale are listed in Table 1. Since the prototype WIR has a very small wall thickness (t/D = 1/40), it's impossible to find a material that satisfies this aspect ratio and keep the structural integrity at the same time. We have tried our best in balancing the designed values and also the manufacturing feasibility.

Generally speaking, the as-built model has a larger axial and bending stiffness compared to the designed values. This may lead to a higher natural frequency of the as-built model, and therefore, the riser response mode may be underestimated in the model test. Meanwhile, the Reynolds number is also much lower in the model test, but with the scaling methodology we adopt in this paper, we have kept the controlling parameter of vessel motion-induced VIV such as *KC* number and riser motion velocity follow the scaling law. Therefore, we are supposed to observe quite similar VIV response as what should happen in the real case scenario. It should be mentioned that the prototype WIR may not respond to exactly the same hydrodynamic responses as the test scaled model, but the observations are useful to better understand and predict the full-scaled riser.

2.2. Experimental setup

Fig. 1 briefly illustrates the WIR model test setup, the deep pit is used to satisfy the designed riser configuration. The top end of the model is pin-connected to a forced motion apparatus, to simulate the vessel motion. It should be noted that there

Table 1
Physical properties of the tested WIR.

Item	Prototype	Model scale (Designed)	Model scale (Measured)
Total Length (m)	1000	38.46	35.66
Outer Diameter (m)	4	0.154	0.165
Inner Diameter (m)	3.9	0.15	0.15
Mass in Air (Kg/m)	1069	1.54	3.61
Bottom Clump Weight (Kg)	181530	10.08	13.53
Bending Stiffness *EI* ($N\cdot m^2$)	1.72E10	1412.34	12022
Tensile Stiffness *EA* (N)	8.68E9	481810	3.3×10^6