Journal of Fluids and Structures 82 (2018) 412–431

Contents lists available at ScienceDirect

Journal of Fluids and Structures

journal homepage: www.elsevier.com/locate/jfs

Evaluation of vortex-induced vibration of a steel catenary riser in steady current and vessel motion-induced oscillatory current

Jungao Wang [a,b], Shixiao Fu [a,*], Rolf Baarholm [c]

[a] State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, Shanghai, China
[b] Department of Mechanical and Structural Engineering and Materials Science, University of Stavanger, Stavanger, Norway
[c] Statoil, Trondheim, Norway

ARTICLE INFO

Article history:
Received 4 December 2017
Received in revised form 2 June 2018
Accepted 31 July 2018

Keywords:
Vortex-induced vibration
Steady uniform current
Vessel motion
Fatigue damage
Travelling waves
Power-in region

ABSTRACT

A large-scale model test of a truncated steel catenary riser (SCR) was performed in an ocean basin to investigate the riser responses under pure steady uniform current and pure vessel motions separately. Out-of-plane vortex-induced vibration (VIV) was confirmed to have occurred under both test conditions. A comparative analysis and discussion were carried out on selected cases in terms of out-of-plane VIV responses, VIV developing mechanisms and the fatigue damage contribution. Results indicate that both steady current-induced and vessel motion-induced VIV responses are dominated by strong travelling waves, but vessel motion-induced VIV responses are more 'intermittent' with respect to the response amplitude and frequency owing to its space- and time-varying shedding frequency. 'Power-in' regions are further estimated to understand the VIV developing mechanisms for both test conditions. Finally, fatigue damages are evaluated showing the damage by vessel motion-induced VIV is comparable and at the same level as uniform current-induced VIV, which highlights the great importance of vessel motion-induced VIV, which cannot be neglected in the design and analysis for SCR systems.

Nomenclature

D	Outer diameter [m]
EI	Bending stiffness [N·m^2]
EA	Tensile stiffness [N]
φ	Hang-off angle [°]
ε	Strain
T_{Axial}	Top axial tension [N]
f_n	nth natural frequency [Hz]
A_{im}	Scaled top imposed motion amplitude at real hang-off point [m]
T_{im}	Scaled top imposed motion period at real hang-off point [s]
f_{im}	Scaled top imposed motion frequency at real hang-off point [Hz]

* Corresponding author.
E-mail address: shixiao.fu@sjtu.edu.cn (S. Fu).

https://doi.org/10.1016/j.jfluidstructs.2018.07.018
0889-9746/

KC	KC number
A_n	Local oscillatory displacement amplitude [m]
V_c	Current velocity [m/s]
θ	Incident angle of the current [°]
V_{norm}	Normal velocity amplitude [m/s]
V_{wave}	Travelling wave speed [m/s]
R	Cross-correlation
St	Strouhal number, 0.2 in this paper [s]
f_{st}	Shedding Frequency [Hz]
f_{resp}	Dominant response Frequency [Hz]
f^*	Non-dimensional frequency
N	Number of cycles to failure
Dam	Damage of each stress range
$\log \overline{a}$	Intercept at the log N-axis by the S–N curve
m	Negative inverse slope of the S–N curve
Num	Quantity of total stress ranges
$\Delta\sigma$	Stress range [Pa]

1. Introduction

As oil and natural gas exploration and production extend to increasingly deep waters, the cost of the riser systems and technological challenges increase rapidly. The use of compliant risers such as steel catenary riser (SCR) and steel lazy wave riser (SLWR) are potential solutions for deep-water production systems (DNV, 2010). An SCR is a prolongation of a sub-sea pipeline attached to a floating production structure in a catenary configuration. The first SCR was installed by Shell in the Auger tension leg platform (TLP) in 1994 at a water depth of 872 m (Basim, 2001). Compared to the straight flexible riser, SCR is characterized with its catenary configuration which is supposed to withstand a larger vessel motion. However, a large vessel motion and touch down point (TDP) variation would lead to more complicated designing issues for SCR systems. SCR lines are commonly subjected to fatigue loads, particularly in the touch down zone, due to wave, current and vessel motion. For the loads from wave and vessel motion on SCRs, there are mature commercial software capable of predicting them (OrcaFlex, 2012; Riflex, 2011).

When the riser is exposed to fluid flow, vortices are generated in the wake of the riser. The alternate vortex shedding would lead to oscillating cross-flow (CF) and in-line (IL) forces, which cause the riser to vibrate perpendicularly and in-line to the ambient flow. Such vibrations are called vortex-induced vibrations (VIVs), which may lead to rapid accumulation of fatigue damage of the riser system, and VIV is also known to amplify drag forces. These issues for a common straight flexible riser have been studied in depth over the last three decades (Griffin and Vandiver, 1984; Lie and Kaasen, 2006; Fang, Niedzwecki, Fu, Li and Yang, 2014; Allen and Henning, 2001; Tognarelli et al., 2001; Niedzwecki and Fang, 2013; Chaplin et al., 2005; Trim et al., 2005; Vandiver et al., 2005; Niedzwecki and Fang, 2013; Baarholm et al., 2006; Fang and Niedzwecki, 2013; Fang, 2013). For current-induced VIV on SCRs, the pioneering experimental work was conducted by Halse and Mo at Marintek in 1998 on an SCR (without flow line) in uniform current considering different incident angles and wave effects (Halse et al., 1999). Their results reveal that current-induced VIV was mostly single mode dominated and the existence of waves could reduce VIV to some extent. Morooka conducted a small-scale SCR model test with the scale factor at 250 in the uniform current, they found that out-of-plane VIV was dominated by strong travelling waves (Morooka and Tsukada, 2013).

VIV can also occur at the sag–bend of an SCR or other types of highly compliant rigid (HCR) risers due to the vessel motion such as heave (Grant et al., 2009). This phenomenon occurs because the riser will be exposed to oscillatory flow due to its motions in still water and further experience intermittent out-of-plane vibration under oscillatory flow. Gonzalez (2001) was the first to perform the indoor large-scale vessel motion-induced VIV model test. 48 out-of-plane forced motion cases with different amplitudes and frequencies were applied to the top end of the SCR. However, only the top reaction force was measured since the outside diameter was too small (5 mm) for local instrumentations. Results revealed that resonance was observed when there was a match between at least two of the following frequencies: riser natural frequency, average shedding frequency or a multiple of the top motion frequency. Cunff (2005) named such phenomena as heave-induced lateral motion (HILM), they conducted a scaled SCR model test with KC numbers within 30. Underwater cameras were installed to capture the motion/vibration near the TDP. Results indicate the response frequency was either at the top exciting frequency or its harmonics. Rateiro et al. (2013) performed similar model tests on scaled SCR model also with small KC numbers within 30. He studied the local motion trajectories of the SCR using an underwater optical tracking system.

To further improve the understanding of VIV effects on SCR systems, a series of experiments have been carried out in the ocean basin at Shanghai Jiao Tong University focusing on both steady uniform current-induced VIV and vessel motion-induced VIV. These two test conditions use the same riser model and experimental setup (Wang et al., 2014a, b). The current was simulated by synchronously towing both top and bottom end of the SCR, and vessel motions were simulated