IOP Conference Series: Materials Science and Engineering

Vortex-induced vibration (VIV) effects of a drilling riser due to vessel motion

To cite this article: R S Joseph *et al* 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* **276** 012013

Vortex-induced vibration (VIV) effects of a drilling riser due to vessel motion

R S Joseph, J Wang*, M C Ong and J B Jakobsen

Department of Mechanical and Structural Engineering and Materials Science,
University of Stavanger, Norway

* Contact author: jungao.wang@uis.no

Abstract. A marine riser undergoes oscillatory motion in water due to the vessel motions, known as global dynamic response. This to-and-fro motion of the riser will generate an equivalent flow that can cause Vortex-Induced Vibrations (VIVs), even in the absence of the ocean current. In the present work, full-scale measurement data of a drilling riser operating in the Gulf of Mexico are analysed. The VIV occurrences for the riser are identified from the data and the possible excitation sources are discussed. The oscillatory flow due to vessel motion is compared with the ocean current and its possibility to excite VIV is analysed. The full-scale data analysis provides an insight into the vessel motion-induced VIV of marine risers in the actual field environment.

1. Introduction

When slender marine structures like risers, free spanning pipelines and mooring lines are exposed to a current flow, they may experience oscillations or vibrations caused by the shedding of vortices around the structure. These are called Vortex Induced Vibrations (VIVs). A cylinder in still water will have many natural frequencies (f_n), for the different modes of vibrations. When the cylinder is exposed to a flow, vortex shedding occurs with a shedding frequency f_s. When the shedding frequency approaches one of the natural frequencies of the cylinder, there is resonance and the cylinder vibrates with a larger amplitude. The frequency of the response is approximately equal to the shedding frequency and the natural frequency. This is called as "lock-in". Once we have a "lock-in", the cylinder is said to experience VIV.

When a marine riser attached to a vessel moves back and forth in water due to the motion of the vessel, an equivalent oscillating current is generated and is experienced by the riser. This equivalent current flow can cause VIV similar to that caused by the ocean current. The vessel motion-induced VIV is influenced by the Keulegan-Carpenter (KC) number values along the riser.

The vessel motion-induced VIV was first reported in STRIDE, a Joint Industry Project focused on compliant risers [1]. It was further studied by Gonzalez [2], Le Cunff et al. [3] and Rateiro et al. [4]. Many investigations based on model tests were later conducted to study the VIV of a free-hanging riser under oscillatory motion. Kwon et al. [5] conducted experiments on a riser model under oscillatory motion for KC numbers as low as 2.24. Wang et al. [6] did similar a study with an 8 m long free-hanging riser subjected to pure vessel motion. The equivalent current velocity, effect of KC number and the characteristics of the VIV responses were investigated. The Cross-Flow (CF) VIV was observed for a KC number as low as 12. Small KC number cases are important given the fact that they can cause considerable fatigue to the riser.

An empirical method to predict the vessel motion-induced VIV of a riser under small KC numbers (KC<40) is proposed by Wang et al. [7]. This model takes into account the KC number distribution along the riser, the vessel motion frequency and the Strouhal relationship to predict the VIV response frequency. Under small KC numbers, the VIV response is no longer governed by the Strouhal relationship using St=0.2, which is valid for the steady current, but by the ratio N between the response frequency, f_{resp} and the vessel motion frequency, f_{im}. The values of the integer N for various KC regimes are documented by Sumer [8] and are shown in equation (1). It was observed that the value of N increases step-wise with the KC number. N is found to increase by 1 with an increase of 8 in KC number.

$$N = \frac{f_{resp}}{f_{im}} = \begin{cases} 2; & 7 < KC < 15 \\ 3; & 15 < KC < 24 \\ 4; & 24 < KC < 32 \\ \cdots & \end{cases} \tag{1}$$

If the KC regime and the vessel motion frequency are known, the response frequency can be estimated using the value of N corresponding to that KC regime.

Wu et al. [9] proposed an empirical model for the prediction of heave-induced VIV. This model considers several time windows within one motion period. The flow velocities over the length of the riser are calculated and a number of velocity snapshots at equal intervals over a period of oscillation are obtained. Each velocity snapshot, taken at a particular time instant over the length of the riser, is the equivalent flow profile for the VIV analysis. Responses for each flow profile are obtained and the average of all these responses is taken to describe the time-varying response of the whole riser.

Many of the investigations focusing on the vessel motion-induced VIV were based on the scaled model tests, performed in controlled laboratory conditions. To the authors' knowledge, no attempts have been made so far to study this phenomenon in an actual field environment. In the present paper, the full-scale measurements from a drilling riser are analysed and instances of VIV are identified. The possible excitation sources including ocean current and vessel motion are investigated. Furthermore, the uncertainties associated with the data analysis are highlighted.

2. Full-scale measurements of drilling riser

Full-scale measurements of a drilling riser were taken by British Petroleum during a drilling campaign in the Gulf of Mexico between 13th April 2007 and 11th July 2007. The dataset is donated to the VIV Data Repository hosted by the Center for Ocean Engineering at MIT, for the purpose of calibration and benchmarking of a VIV software [10] and is publicly accessible. The main parameters in the data set are the accelerations measured by the accelerometers at various points along the span of the riser. The dataset contains the following:

- Riser configuration, dimensions and riser weight.
- Tension and mud weight data.
- Current data at different water depth.
- Acceleration data at various points along the riser.

2.1. Riser configuration and instrumentation

Two wells were drilled during the drilling period. The configuration of the riser during drilling of well-1 is illustrated in Figure 1. The instrumentation consists of 13 standalone loggers. One of the loggers is located on the drill floor and measures the vessel acceleration. The remaining loggers are placed at various locations along the riser. The measurement loggers are named as S01, S02, ..., S13 with S01 situated on the drill floor. Their locations are indicated by the squares in Figure 1. It can be seen that the majority of the loggers are concentrated towards the lower end of the riser. Such an arrangement is to capture all the expected modes with a minimum possible number of loggers. An optimum placement of loggers should capture at least the quarter wavelength of the lowest mode expected [11]. The logger contains the sensors, batteries, memory card and all the associated electronics encased within a cylindrical casing [10]. The loggers are strapped to the structure. Typically, motion sensors are made of tri-axial accelerometers and tri-planar angular rate sensors [12], but the angular rate sensors are not active in this experiment.

The top tension applied to the riser is 8408 kN and the average density of mud used during the drilling period is 1580 kg/m^3. The properties of the riser sections are provided in table 1. The modulus of elasticity of the material is 2.07 x 1011 N/m^2 and the density is 7850 kg/m^3. The eigenmodes of the riser are shown in Figure 2.

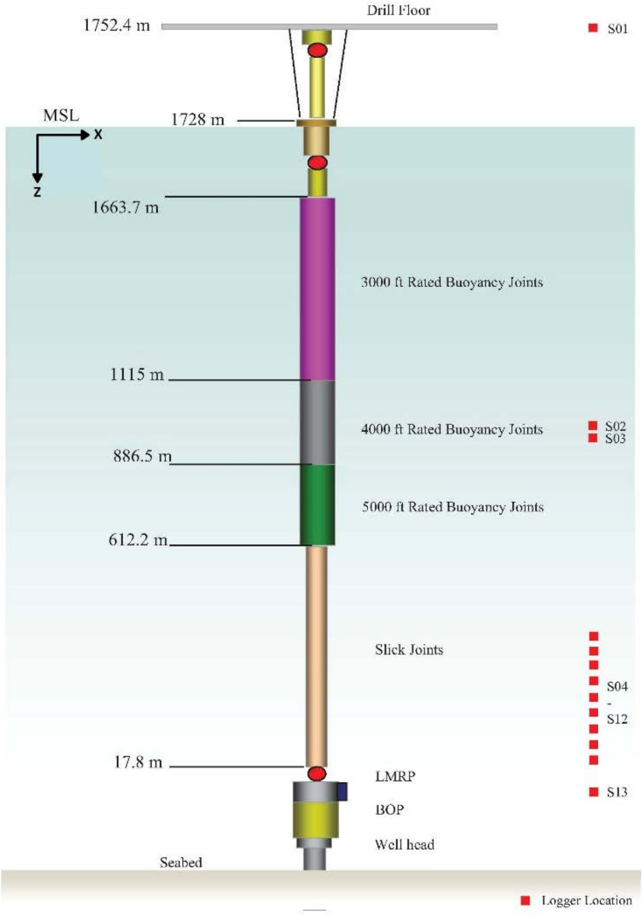

Figure 1. Configuration of the drilling riser for well-1 [10].

2.2. Environment and current data

The water depth at the location of well-1 is 1728 m and well-2 is 1729 m. The current at the location was measured using three ADCPs (Acoustic Doppler Current Profiler), two of which are mounted on the vessel. The current is sampled at every 10 minutes [10]. A constant density of 1025 kg/m^3 is assumed for the sea water.

2.3. Accelerations and events

The translational acceleration data are recorded continuously for a duration of 15 minutes at each 2 hour interval. This limited duration of measurements is adopted in order to distribute a limited battery life over the whole drilling period. The sampling frequency is 10 Hz. Each 15-minute-long recording period is termed as an event. There are a total of 1078 events captured during the drilling period, spread over 3 operational conditions – (1) drilling of well-1, (2) hang-off and transport and (3) drilling of well-2.

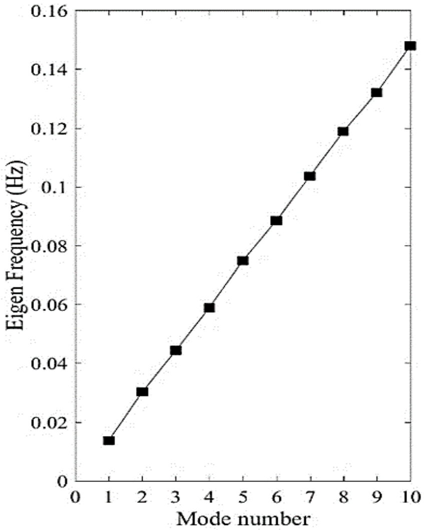

Figure 2. Eigenmodes and eigen frequencies for the riser.

Table 1. Riser sections and properties.

Description	L (m)	Stress diameter (m)	Thickness (m)	Hydrodynamic diameter (m)	Unit dry weight (kg/m)	Unit submerged weight (kg/m)	Bending stiffness EI (Nm^2)	Axial stiffness EA (N)
Diverter	4.1	0.5334	0.02	0.5334	3114.72	-	2.27 x 10^8	6.88 x 10^9
16.7 ft pup joints	5.1	0.5334	0.02	0.5334	706.76	614.88	2.27 x 10^8	6.88 x 10^9
Inner barrel	9.2	0.5334	0.02	0.5334	787.95	-	1.79 x 10^8	5.34 x 10^9
Outer barrel	30.4	0.6604	0.04	0.6604	863.10	750.89	7.49 x 10^8	1.54 x 10^{10}
Intermediate FJ	2.8	1.1938	0.35	1.1938	1904.01	1656.52	2 x 10^{10}	1.92 x 10^{11}
Termination joint	17.3	0.5334	0.02	0.5334	735.95	640.28	2.27 x 10^8	6.88 x 10^9
5 ft pup joints	1.5	0.5334	0.02	0.5334	1391.46	1210.49	2.27 x 10^8	6.88 x 10^9
20 ft pup joints	6.1	0.5334	0.02	0.5334	740.75	644.46	2.27 x 10^8	6.88 x 10^9
40 ft pup joints	12.2	0.5334	0.02	0.8636	614.44	534.56	2.27 x 10^8	6.88 x 10^9
3000 ft buoyancy joints	548.6	0.5334	0.02	1.2827	861.72	17.62	2.27 x 10^8	6.88 x 10^9
4000 ft buoyancy joints	228.6	0.5334	0.02	1.3081	904.98	27.54	2.27 x 10^8	6.88 x 10^9
5000 ft buoyancy joints	274.3	0.5334	0.02	1.3335	957.82	15.04	2.27 x 10^8	6.88 x 10^9
Slick joints	594.5	0.5334	0.02	0.8636	586.74	510.47	2.27 x 10^8	6.88 x 10^9
Lower FJ	2.7	1.4732	0.49	1.4732	2485.25	933.04	4.73 x 10^{10}	3.13 x 10^{11}
LMRP	3.4	5.6515	2.58	5.6515	29495.64	25661.20	1.04 x 10^{13}	5.15 x 10^{12}
BOP	7.2	5.6515	0.02	5.6515	26597.42	23139.76	1.04 x 10^{13}	5.15 x 10^{12}
Wellhead	4.4	0.9652	0.06	0.9652	1854.08	1613.09	3.49 x 10^9	3.37 x 10^{10}

3. Identification of VIV from the data

The VIV and the corresponding response frequency can be identified by performing a spectral analysis of the accelerations or displacements at each logger location. Figure 3 shows the acceleration spectrum at a particular logger. The responses seen on the spectrum can also be due to sources other than VIV such as drill string rotation or wave-induced motion [13]. VIV occurs in a narrow range of low frequencies. Higher frequency vibrations caused by drill string rotation can be identified based on the rotation speeds and can be discarded by passing the signal through a low-pass filter.

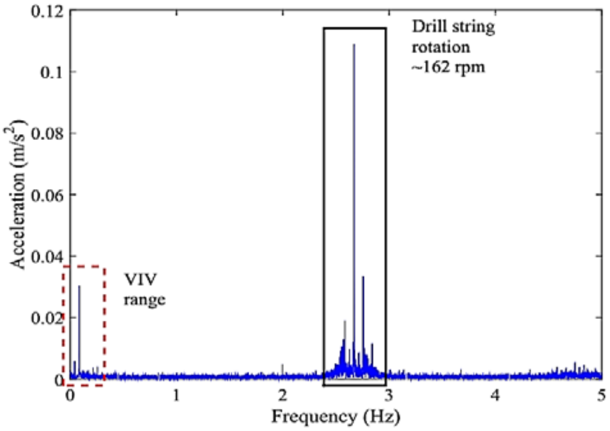

Figure 3. Acceleration spectrum in X direction at a logger showing VIV and other high frequency vibrations (Event dated 17/04/2007 1800 hrs).

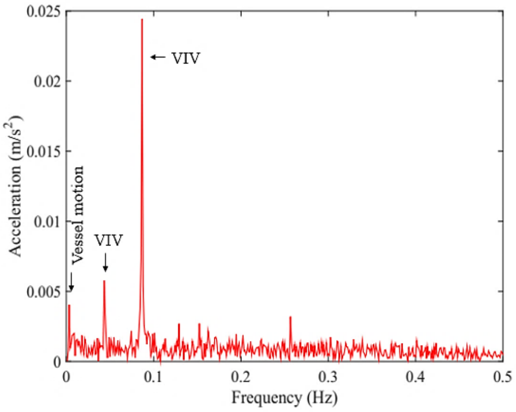

Figure 4. Acceleration spectrum in X direction at a logger showing peaks in the VIV range (Event dated 17/04/2007 1800 hrs).

Figure 4 shows the acceleration spectrum at low frequencies. The VIV response can be found by correlating the spectral peaks in the VIV range across all the loggers on the riser. The vessel motion occurs at very low frequencies and can be easily identified from a displacement spectrum. The displacement spectrum gives a very large peak for the vessel motion frequency at all the loggers. This can be correlated with logger S01 which measures the vessel acceleration and hence vessel motion frequency can be singled out.

In this section, a representative event from the full-scale data, measured on 17/04/2007 at 1800 hrs, is analysed. This corresponds to the riser configuration for the drilling of well-1. The acceleration signals are passed through a low-pass filter to filter-in signals in the VIV range and lower frequencies (< 0.5 Hz).

Figure 5 represents the spectra of accelerations in X direction across all the 13 loggers. Figure 6 represents those in the Y direction. In both directions, it can be seen that all the loggers except S01 (S01 measures vessel acceleration) have a peak response at a frequency of 0.0866 Hz. This is identified to be the response frequency of the VIV. S01 has a peak at a lower frequency which corresponds to the frequency of the vessel motion. Figure 7 shows the displacement amplitude spectrum of logger S01 which is attached to the vessel. Since it measures purely the motion of the vessel and not the VIV, the peak of the spectrum should provide us with the frequency of the vessel motion. In this way, the frequency of the vessel motion can be identified. From the figure, we can see that the vessel motion frequency is 0.0033 Hz, which is reasonable for a MODU's slow varying motion due to the second order differential frequency wave loads.

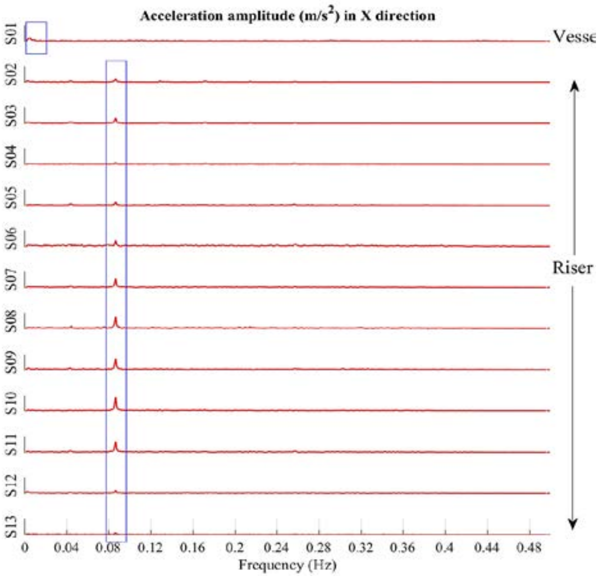

Figure 5. Spectra of acceleration in X direction across all loggers.

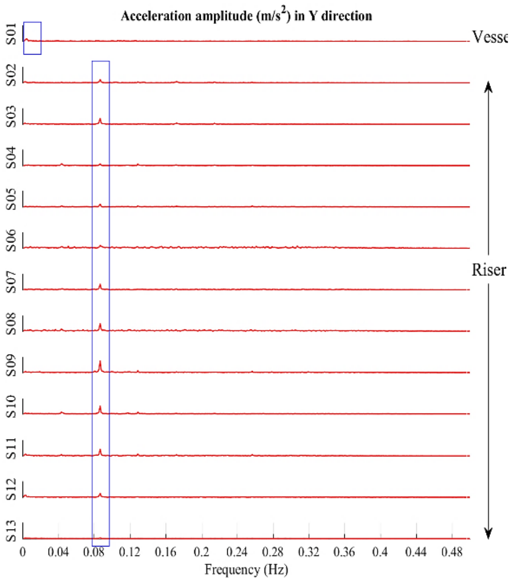

Figure 6. Spectra of acceleration in Y direction across all loggers.

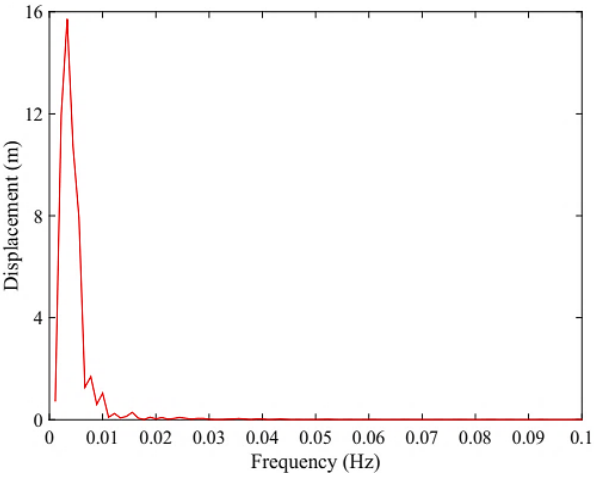

Figure 7. Displacement spectrum in X direction of logger S01.

The source of excitation of the VIV can be either the ocean current or the oscillatory flow due to the vessel motion. From the data, the ocean current details for this case are available up to a depth of 800 m. The direction of the current is at 136-196° w.r.t vessel bow.

3.1. Comparison of current profiles

3.1.1. Equivalent current profile: In order to describe the vessel motion-induced VIV, it is necessary to define the equivalent current that causes it. Equivalent current profile is the one that the riser “sees” due to its relative motion in the water. Since the vessel motions are oscillatory in nature, the movement of the riser results in time-varying velocity series at each point along its span. The representative maximum of the velocity at each point can be used to create a current profile.

In case of irregular vessel motions, Wang et al. [14] have proposed a method to generate the equivalent current profile in which the standard deviation of the velocity time series at each point along the length of the riser is multiplied by √2 to get the representative maximum. Hence the time-varying velocity can be simplified into an equivalent current profile according to equation (2).

$$V_e(z) = \sqrt{2} \times \sigma_v(z) \tag{2}$$

where $V_e\ (z)$ is the equivalent current profile and $\sigma_V\ (z)$ is the standard deviation of the time-varying velocity series at each point along the length.

Following steps are used to formulate the equivalent current profile in this case:

- The acceleration data is passed through a low-pass filter to filter-in the low frequencies (<0.04 Hz) which are associated with the vessel motion.
- The velocities in X and Y directions at each logger are derived by the integration of accelerations in X and Y respectively.
- The derived velocities are detrended after the integration to keep the dynamic part.
- The resultant of the velocities in X and Y is obtained. The standard deviation of the resultant velocity time series is found out at each logger and used in equation (2) to obtain the equivalent current profile.

It should be mentioned that the vessel and the riser are moving/vibrating in both X and Y directions. It is also hard to figure out the correlation among different sensors, partly because of the misalignment of the sensors. Therefore, the resultant of the velocities from both directions are taken when estimating the equivalent current profile, which should be on the conservative side which helps to negate any errors in the data due to the possible logger misalignments.

In Figure 8, the obtained equivalent current profile due to the motion of the vessel is compared with the ocean current. It is seen that the ocean current velocities are very low compared with the equivalent velocities from the vessel motion. The ocean current has a maximum value of 0.2 m/s, whereas the current speeds in the equivalent current profile are much higher owing to the higher velocities of the vessel's lateral motions. At the top of the riser, the velocity is as high as 0.95 m/s. The bottom part of the riser experiences a higher velocity due to the high accelerations.

Figure 9 shows the resultant KC number distribution for the drilling riser in this case. KC number is defined as follows:

$$KC\ (z) = \frac{2\pi A_n(z)}{D} \tag{3}$$

where $A_n(z)$ is the resultant displacement of the riser at a node and D is the diameter of the riser. The displacements are obtained by integrating the velocities. It is seen that the KC numbers are high for this case owing to the high amplitudes of vessel drifts.

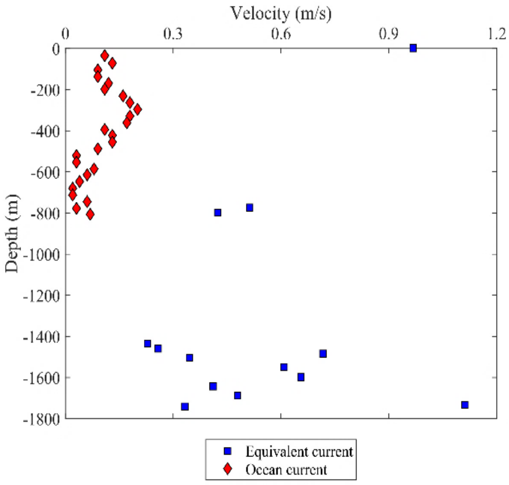

Figure 8. Generated equivalent current profile and the ocean current profile.

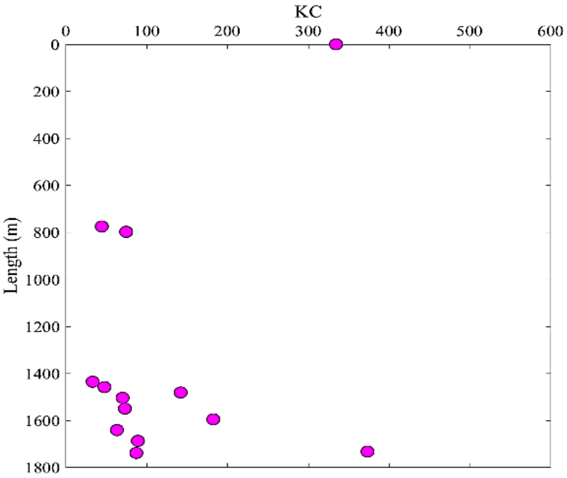

Figure 9. Resultant KC number distribution along the riser.

3.2. *Numerical analysis*

Both the current profiles are used as input in VIVANA to predict the VIV response frequency. Since the ocean current data is not available below a depth of 800 m, the profile is extrapolated to zero velocity at the bottom. A constant Strouhal number of 0.2 is used in the analysis. Figure 10 shows the comparison of the excitation frequencies along the riser due to the ocean current and the equivalent current due to vessel motion. This, in turn, is compared with the averaged spectrum of acceleration in X direction from all the loggers. It can be seen that the response frequency due to ocean current lies in a low range of 0-0.04 Hz, whereas that due to the equivalent current lie in a range of 0.06-0.11 Hz. The latter frequency range is closer to the peak of the observed acceleration spectrum. This is an indication that the equivalent current could excite the VIV. Although not dominant, a smaller peak is also visible at around 0.04 Hz in the spectrum.

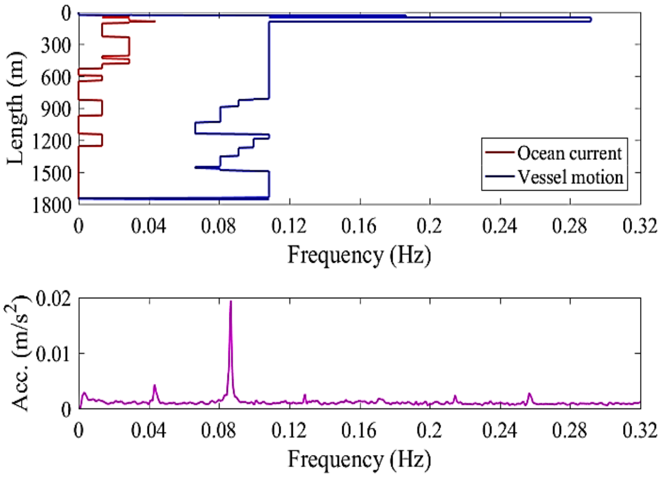

Figure 10. Comparison of excitation frequencies from VIVANA analysis with averaged acceleration spectrum in X direction.

3.3. Major uncertainties in the analysis

The complexity of the measurements and lack of information makes it difficult to interpret the data and ascertain whether the observed VIV is due to ocean current or vessel motion. Some of the uncertainties associated with the full-scale measurements and analysis are presented in this section.

A major uncertainty here is in the identification of the vessel motion frequency. The frequency resolution of the measurements is 0.001 Hz. Due to lack of vessel data or mooring details, it was difficult to ascertain the reasonableness of the obtained vessel motion frequencies. Also, the fact that the duration of measurements is only 15 mins adds to uncertainty in the obtained results. Prior works by Tognarelli et al. [13] and Thethi et al. [12] based on riser monitoring data were focused only on finding the response in the VIV frequency range. Typically, the accelerometers are not accurate at low frequencies, but the vessel displacements obtained by integration is within the range of typical vessel drifts.

The response obtained from the measurements is at a frequency of 0.0866 Hz. This falls in the typical wave frequency range. Information regarding the waves is not available and hence it was not possible to determine the effect of waves on the vessel and the riser.

The alignment of the axes of the loggers with the global axes is not guaranteed and hence there is uncertainty in the data. Also, it could be possible that the measurements are contaminated by gravity due to the bending motion of the riser.

The ocean current velocities are available only up to a depth of 800 m and had to be interpolated to zero at the bottom. The effect of ocean current on the vessel motion-induced VIV has not been considered here owing to the large difference in speeds between it and the equivalent current. A relative speed is only negligibly more/less than the speed of the equivalent current, especially at greater depths. For other cases when the equivalent current and the ocean current are closer in amplitude, it is hard to draw the same conclusion. More controlled model test should be designed and performed in order to find the effect of the ocean current on vessel motion-induced VIV, especially when the vessel motion is irregular and three-dimensional as have been observed from the full-scale measurement

4. Conclusion and scope of future work

Full-scale measurement data from a drilling riser was analysed in this study. VIV was identified from the data. The ocean current and the equivalent current caused by the vessel motion were used to predict the VIV. The equivalent current was found to excite VIV with a response frequency closer to the observations than the ocean current, which points out to the possibility of occurrence of vessel motion-induced VIV. The uncertainties associated with the field measurements and analysis makes it difficult to ascertain the actual source of excitation.

There remains scope for future work where model tests could be designed and performed for irregular vessel motion cases to obtain a thorough understanding of the phenomenon involved.

Acknowledgments

This work has been partly funded by the Program Area for Research “Computational Methods in Offshore Technology (COTech)” at Faculty of Science and Technology, University of Stavanger, Norway. The authors thank the Faculty of Science and Technology for supporting this work.

References

[1] Willis N R T and Thethi K S 1999 Stride JIP: Steel risers in deepwater environments – progress summary *Proc. of Offshore Technology Conf. (Houston).*

[2] Gonzalez E C 2011 High frequency dynamic response of marine risers with application to flow induced vibration *Massachusetts Institute of Technology*.

[3] Cunff C, Biolley F and Damy G 2005 Experimental and numerical study of heave- induced lateral motion (HILM) *Proc. of 24th Int. Conf. on Ocean, Offshore and Arctic Engineering (Halkidiki).*

[4] Rateiro F, Goncalves R T, Pesce C P, Fujarra A L C, Franzini G R and Mendes P 2013 A model scale experimental investigation on vortex-self induced vibrations (VSIV) of catenary risers *Proc. of 32nd Int. Conf. on Ocean, Offshore and Arctic Engineering (Nantes).*

[5] Kwon Y J, Kim H J and Jung D H 2015 A study for forced oscillation experiment for OTEC riser under current *Proc. of 25th Int. Ocean and Polar Engineering Conf. (Kona)*.

[6] Wang J, Fu S, Ong M C and Li H 2016 Experimental investigation on vortex- induced vibration of a free-hanging riser under vessel motion *Proc. of 35th Int. Conf. on Ocean, Offshore and Arctic Engineering (Busan).*

[7] Wang J, Joseph R S, Ong M C and Jakobsen J B 2017 Numerical investigation on vessel motion-induced VIV for a free hanging riser under small Keulegan–Carpenter numbers *Proc. of 36th Int. Conf. on Ocean, Offshore and Arctic Engineering (Trondheim)*.

[8] Sumer M B and Fredsøe J 2006 *Hydrodynamics Around Cylindrical Structures* (World Scientific Publishing Company).

[9] Wu J, Lie H, Larsen C M and Baarholm R J 2015 An Empirical Heave Induced VIV Prediction Model *Proc. of 34th Int. Conf. on Ocean, Offshore and Arctic Engineering (St. John's)* .

[10] BP and 2H Offshore 2008 VIV benchmarking repository–drilling riser without VIV suppression Data P*ackage Technical Note*.

[11] Natarajan S, Howells H, Deka D and Walters D 2006 Optimization of sensor placement to capture riser VIV response *Proc. of 25th Int. Conf. on Ocean, Offshore and Arctic Engineering (Hamburg).*

[12] Thethi R, Howells H, Natarajan S and Bridge C 2005 A fatigue monitoring strategy and implementation on a deepwater top tensioned riser *Proc. of 2005 Offshore Technology Conf. (Houston).*

[13] Tognarelli M A, Taggart S and Campbell M 2008 Actual VIV fatigue response of full scaledrilling risers: with and without suppression devices *Proc. of 27th Int. Conf. on Ocean, Offshore and Arctic Engineering (Estoril).*

[14] Wang J, Jaiman R K, Adaikalaraj P F, Shen L, Tan S B and Wang W 2016 Vortex-induced vibration of a free-hanging riser under irregular vessel motion *Proc. of 35th Int. Conf. on Ocean, Offshore and Arctic Engineering (Busan).*