### MASTER'S THESIS

<table>
<thead>
<tr>
<th>Study programme/specialisation:</th>
<th>Spring semester, 2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>Master of Science in Offshore Technology,</td>
<td>Open/Confidential</td>
</tr>
<tr>
<td>Marine and Subsea Technology</td>
<td></td>
</tr>
</tbody>
</table>

| Author: Rohan Shabu Joseph                            | ................................................................. |
|                                                     | (signature of author) |

| Supervisor: Prof. Muk Chen Ong                        |                       |
| Co-supervisors: Dr. Jungao Wang, Prof. Jasna Bogunovic Jakobsen |

<table>
<thead>
<tr>
<th>Title of master's thesis:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Numerical Investigation on the Vortex-Induced Vibration Effects of a Deep Sea Mining Riser</td>
<td></td>
</tr>
</tbody>
</table>

| Credits (ECTS): 30                                    |                       |

| Keywords:                                             |                       |
| VIV, Deep sea mining, Marine riser, Vessel motion, Response frequency model |                       |

| Number of pages: 108                                   |                       |
| + supplemental material/other: 15                      |                       |

Stavanger, 14 June 2017
(This page intentionally left blank)
Numerical Investigation on the Vortex-Induced Vibration Effects of a Deep Sea Mining Riser

Rohan Shabu Joseph

Spring 2017

MASTER THESIS
Department of Mechanical and Structural Engineering and Materials Science
University of Stavanger

Main supervisor: Prof. Muk Chen Ong
Co-supervisors: Dr. Jungao Wang
Prof. Jasna Bogunović Jakobsen
Abstract

In recent times, the deep sea mining industry has attracted growing attention globally as it targets mining activities in deeper waters of up to 6,000 m depth. Many of the technologies used in deep sea mining have been adopted from the offshore oil and gas industry. A self-propelled Seaﬂoor Production Tool (SPT) is placed on the sea bottom and collects minerals from the seabed. These are then transported to the surface vessel through a Riser and Lifting System (RALS). The lift is achieved by either pneumatic or hydraulic means.

The major part of the RALS is the vertical riser that runs from the vessel and is connected to the SPT via a ﬂexible hose, which decouples the relative motion between the riser and the SPT. Since the restriction by the ﬂexible hose is relatively negligible, the bottom of the riser is free to move and large motions are expected under top vessel motion. As in the case of offshore oil and gas industry, the design, analysis and maintenance of the riser (major part of RALS) is one of the most challenging task.

One major issue for the marine riser is the vortex-induced vibrations (VIVs) caused by the shedding of vortices by the ﬂow around the riser. The back and forth motion of the riser in the water due to the vessel motion can also generate an equivalent oscillatory ﬂow which can cause VIV (Wang et al., 2016b). The present work aims to study the VIV effects due to vessel motion on a deep sea mining riser. An empirical model is proposed to predict the VIV response of a riser under vessel motions of low Keulegan-Carpenter (KC) numbers with the vessel motion conditions under a fatigue sea-state. Numerical method validation was carried against model test results and full-scale measurement data. The results of the validation were used to ﬁne tune the model for predicting the VIV response of an ultra-long mining riser under vessel motions. Since the vessel motion-induced VIV would cause similar stresses and fatigue damage as the current induced VIV (Wang et al., 2016b), a fatigue damage analysis of the riser due to vessel motion induced VIV is also conducted. Further, VIV due to ocean current is also investigated and compared with the VIV due to vessel motions.
Acknowledgement

This thesis has been submitted in partial fulfillment of the requirement for completing the degree of Master of Science in Offshore Technology at the University of Stavanger.

I take this opportunity to express my gratitude to all those who have provided me with valuable guidance and support.

First of all, I would like to thank my supervisor Prof. Muk Chen Ong for giving me this opportunity to work on this challenging and interesting topic. His constant motivation and encouragement helped me a lot towards the completion of this work.

I would like to extend my heartfelt gratitude to Dr. Jungao Wang, whose valuable advices and inputs were the key for the completion of this thesis. Despite his busy schedule, he took time to review my progress and was always available to guide me with his inputs and suggestions. Without his comments and remarks, this thesis report would not have been perfected. I would also like to thank Prof. Jasna Bogunović Jakobsen for her feedback on the work in this thesis.

I would like to express my deepest thanks to Dr. Lin Li for helping me with her expertise in the areas of vessel motion and mooring systems. Also, I would like to thank Dr. Etienne Cheynet for his valuable inputs regarding accelerometers and acceleration data.

I gratefully acknowledge BP and MIT for sharing the full-scale measurement data in the VIV Data Repository hosted by Center for Ocean Engineering, MIT.

Finally, I would like to thank my parents and my friends for their affection and support during my stay in Stavanger.
Contents

Abstract ................................................................. i
Acknowledgement ....................................................... ii

1 Introduction .......................................................... 1
  1.1 Background and Motivation ...................................... 1
  1.2 Objectives ......................................................... 4
  1.3 Outline of the Thesis ............................................. 4

2 Theory ................................................................. 7
  2.1 Vortex Shedding and Vortex Induced Vibration .................. 7
     2.1.1 Vortex shedding ............................................. 7
     2.1.2 Vortex induced vibration and lock-in ....................... 8
  2.2 Governing Physical Parameters of VIV ........................... 9
     2.2.1 Reynolds number ............................................. 9
     2.2.2 Vortex shedding frequency .................................. 10
     2.2.3 Mass ratio ................................................... 12
     2.2.4 Reduced velocity ............................................ 12
     2.2.5 Keulegan-Carpenter (KC) number ............................ 13
  2.3 Semi-empirical VIV Prediction Method ........................... 15

3 Empirical Model for Prediction of Vessel Motion-induced VIV .... 19
  3.1 Introduction ...................................................... 19
  3.2 Proposed Empirical Prediction Model ............................. 21
     3.2.1 Equivalent current profile ................................... 21
3.2.2 Representative KC number ........................................ 24
3.2.3 Response frequency model for low KC number cases .......... 25
3.2.4 VIV prediction for high KC number cases ...................... 27
3.3 Vibration Amplitudes for Irregular Motions ...................... 28

4 Empirical Model Validation: Against Model Test Results 29
4.1 Introduction ............................................................. 29
4.2 Methodology ............................................................ 29
4.3 Validation Based on Water Intake Riser Model Test .............. 30
  4.3.1 Results and discussion ............................................. 31
4.4 Validation Based on Free-Hanging Riser Model Test .......... 36
  4.4.1 Results and discussion ............................................. 37
4.5 Discussion ............................................................... 45

5 Empirical Model Validation: Against Full-scale Measurements 47
5.1 Introduction ............................................................. 47
5.2 Full-scale Data Information ......................................... 48
  5.2.1 Riser configuration .................................................. 48
  5.2.2 Environment and current data ................................... 51
  5.2.3 Instrumentation ...................................................... 51
  5.2.4 Accelerations and events ......................................... 51
  5.2.5 Limitations .......................................................... 52
5.3 Data Analysis ........................................................... 53
5.4 Methodology ............................................................. 55
5.5 Results and Discussion ............................................... 56
  5.5.1 Vessel motion-induced VIV dominant cases ................. 57
  5.5.2 Ocean current-induced VIV dominant cases ................. 71
  5.5.3 Discussion .......................................................... 74

6 Numerical VIV Prediction of Deep Sea Mining Riser 77
6.1 Introduction ............................................................. 77
6.2 Riser Configuration .......................................................... 78
6.3 Simplifications and Assumptions ........................................... 79
6.4 Case Studies ................................................................. 80
   6.4.1 Regular motion case with A=1.5 m ................................ 81
   6.4.2 Regular motion case with A=2.5 m ................................ 86
   6.4.3 Regular motion case with A=5 m .................................. 89
   6.4.4 Irregular motion case .................................................. 93
   6.4.5 Current-induced VIV case .......................................... 98
6.5 Discussion ..................................................................... 100

7 Conclusions .................................................................... 103

Bibliography ..................................................................... 105

A Small-scale Riser Model Tests: Comparison of Eigen Frequencies 109

B Modelling of Drilling Riser ................................................ 111

C Hydrodynamic Coefficients used for Deep Sea Mining Riser 113

D MATLAB Codes for Acceleration Data Analysis .................. 115

E Full-scale Measurement Data Logger Specifications ............... 121
# List of Figures

1.1 Deep sea mineral deposits around the globe (Nautilus Minerals, 2016a) . . . 2  
1.2 Overview of Deep Sea Mining System (Nautilus Minerals, 2016b) . . . . . . 3  

2.1 Cylinder exposed to uniform flow (Goharzadeh and Molki, 2014) . . . . . . 7  
2.2 Mechanism of vortex shedding (Sumer and Fredsøe, 2006) . . . . . . . . . 8  
2.3 Vortex patterns behind a cylinder for various Re regimes . . . . . . . . . . 10  
2.4 Variation of Strouhal number with Reynolds number . . . . . . . . . . . . 11  
2.5 CF response of a cylinder in steady flow . . . . . . . . . . . . . . . . . . . 13  
2.6 Excitation zones along the structure exposed to a shear current . . . . . . . 16  
2.7 Excitation zones along the structure without overlapping frequencies . . . 16  

3.1 Illustration of velocities along the riser . . . . . . . . . . . . . . . . . . . . 21  
3.2 Illustration of Equivalent Current Profile 1 . . . . . . . . . . . . . . . . . . 22  
3.3 Illustration of Equivalent Current Profile 2 . . . . . . . . . . . . . . . . . . 23  
3.4 Illustration of Equivalent Current Profile 3 . . . . . . . . . . . . . . . . . . 24  
3.5 Illustration of representative KC number . . . . . . . . . . . . . . . . . . . 25  
3.6 Flowchart illustrating the empirical frequency response model . . . . . . . . 27  

4.1 Eigen modes and Eigen frequencies of the WIR model . . . . . . . . . . . . 32  
4.2 Normalized mode shapes for the WIR model . . . . . . . . . . . . . . . . . . 32  
4.3 Equivalent current profile for WIR . . . . . . . . . . . . . . . . . . . . . . 33  
4.4 KC number distribution for WIR . . . . . . . . . . . . . . . . . . . . . . . 33  
4.5 Excitation frequencies for WIR . . . . . . . . . . . . . . . . . . . . . . . . 34  
4.6 Response frequency along the riser from experiment for WIR (Wang et al., 2016c) 35
5.14 Comparison of RMS A/D along the riser (Event 58) . . . . . . . . . . . . . . 61
5.15 Equivalent current profile and the ocean current profile (Event 612) . . . . 62
5.16 Spectra of acceleration in X direction across all loggers (Event 612) . . . . 62
5.17 Spectra of acceleration in Y direction across all loggers (Event 612) . . . . 63
5.18 Displacement spectrum of logger S01 (Event 612) . . . . . . . . . . . . . . 63
5.19 KC number distribution along the riser (Event 612) . . . . . . . . . . . . . . 64
5.20 Excitation frequencies vs. displacement spectrum at S05 (Event 612) . . . 65
5.21 Comparison of RMS A/D along the riser (Event 612) . . . . . . . . . . . . . 65
5.22 Equivalent current profile and the ocean current profile (Event 413) . . . . 66
5.23 Comparison of shedding frequencies (Event 413) . . . . . . . . . . . . . . . 67
5.24 Spectra of acceleration in X direction across all loggers (Event 413) . . . . 68
5.25 Spectra of acceleration in Y direction across all loggers (Event 413) . . . . 68
5.26 Displacement spectrum of logger S01 (Event 413) . . . . . . . . . . . . . . 69
5.27 KC number distribution along the riser (Event 413) . . . . . . . . . . . . . . 69
5.28 Excitation frequencies vs. displacement spectrum at S09 (Event 413) . . . 70
5.29 Comparison of RMS A/D along the riser (Event 413) . . . . . . . . . . . . . 70
5.30 Equivalent current profile and the ocean current profile (Event 434) . . . . 71
5.31 Spectra of acceleration in X direction across all loggers (Event 434) . . . . 72
5.32 Spectra of acceleration in Y direction across all loggers (Event 434) . . . . 73
5.33 Excitation frequencies vs. displacement spectrum at S03 (Event 434) . . . . 73
5.34 Comparison of RMS A/D along the riser (Event 434) . . . . . . . . . . . . . 74

6.1 Configuration of the riser . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 78
6.2 Eigenmodes and eigen frequencies for the deep sea mining riser . . . . . . . 80
6.3 Normalized mode shapes for the deep sea mining riser . . . . . . . . . . . . . 81
6.4 Equivalent current profile (regular motion case with A=1.5 m) . . . . . . . 82
6.5 KC number distribution (regular motion case with A=1.5 m) . . . . . . . . 82
6.6 Excitation frequencies (regular motion case with A=1.5 m) . . . . . . . . . 83
6.7 RMS A/D along the riser (regular motion case with A=1.5 m) . . . . . . . . 84
6.8 Strain along the riser (regular motion case with A=1.5 m) . . . . . . . . . . 84
6.9 Fatigue damage along the riser (regular motion case with A=1.5 m) . . . . 85
6.10 Equivalent current profile (regular motion case with A=2.5 m) . . . . . 86
6.11 KC number distribution (regular motion case with A=2.5 m) . . . . . 87
6.12 Excitation frequencies (regular motion case with A=2.5 m) . . . . . 87
6.13 RMS A/D along the riser (regular motion case with A=2.5 m) . . . . 88
6.14 Strain along the riser (regular motion case with A=2.5 m) . . . . . 88
6.15 Fatigue damage along the riser (regular motion case with A=2.5 m) . . 88
6.16 Equivalent current profile (regular motion case with A=5 m) . . . . . 89
6.17 KC number distribution (regular motion case with A=5 m) . . . . . 90
6.18 Excitation frequencies (regular motion case with A=5 m) . . . . . 90
6.19 RMS A/D along the riser (regular motion case with A=5 m) . . . . . 91
6.20 Strain along the riser (regular motion case with A=5 m) . . . . . 92
6.21 Fatigue damage along the riser (regular motion case with A=5 m) . . . 92
6.22 Displacement spectrum of the vessel motion (irregular motion case) . . 93
6.23 Equivalent current profile (irregular motion case) . . . . . . . . . . 94
6.24 The KC number distribution along the riser (irregular motion case) . . 94
6.25 Excitation frequency along the riser (irregular motion case) . . . . . 95
6.26 RMS A/D along the riser (irregular motion case) . . . . . . . . . . 96
6.27 Strain along the riser (irregular motion case) . . . . . . . . . . 97
6.28 Fatigue damage along the riser (irregular motion case) . . . . . . . . 97
6.29 Ocean current profile (current-induced VIV case) . . . . . . . . . . 98
6.30 Excitation frequencies along the riser (current-induced VIV case) . . 99
6.31 Strain along the riser (current-induced VIV case) . . . . . . . . . . 99
6.32 Fatigue damage along the riser (current-induced VIV case) . . . . . 100
### List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Value of the ratio N for various KC regimes (Williamson, 1985)</td>
<td>20</td>
</tr>
<tr>
<td>3.2</td>
<td>Frequency information from experiment (Wang et al., 2016c)</td>
<td>20</td>
</tr>
<tr>
<td>4.1</td>
<td>Properties of model riser (Wang et al., 2016c)</td>
<td>31</td>
</tr>
<tr>
<td>4.2</td>
<td>Riser motions (Wang et al., 2016c)</td>
<td>31</td>
</tr>
<tr>
<td>4.3</td>
<td>Properties of model riser (Wang et al., 2016a)</td>
<td>37</td>
</tr>
<tr>
<td>4.4</td>
<td>Riser motions (Wang et al., 2016a)</td>
<td>37</td>
</tr>
<tr>
<td>5.1</td>
<td>Locations of the loggers</td>
<td>50</td>
</tr>
<tr>
<td>5.2</td>
<td>Events considered for analysis</td>
<td>57</td>
</tr>
<tr>
<td>6.1</td>
<td>Properties of the riser</td>
<td>79</td>
</tr>
<tr>
<td>6.2</td>
<td>Vessel motions for regular motion case with A=1.5 m</td>
<td>81</td>
</tr>
<tr>
<td>6.3</td>
<td>Vessel motions for regular motion case with A=2.5 m</td>
<td>86</td>
</tr>
<tr>
<td>6.4</td>
<td>Vessel motions for regular motion case with A=5 m</td>
<td>89</td>
</tr>
<tr>
<td>6.5</td>
<td>Comparison of case studies</td>
<td>100</td>
</tr>
</tbody>
</table>
List of Abbreviations

ADCP       Acoustic Doppler Current Profiler
CF         Cross Flow
FBG        Fiber Brag Grating
IL         In Line
KC         Keulegan-Carpenter
MSL        Mean Sea Level
RALS       Riser and Lifting System
RMS        Root Mean Square
SMS        Seafloor Massive Sulfides
SPT        Seafloor Production Tool
VIV        Vortex-Induced Vibration
WIR        Water Intake Riser

List of Symbols

\(f_n\)  Natural frequency
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_v$</td>
<td>Vortex shedding frequency</td>
</tr>
<tr>
<td>$f_{dom}$</td>
<td>Dominant response frequency</td>
</tr>
<tr>
<td>$f_{im}$</td>
<td>Imposed motion/Vessel motion frequency</td>
</tr>
<tr>
<td>$f_{resp}$</td>
<td>Response frequency</td>
</tr>
<tr>
<td>$St^*$</td>
<td>Equivalent Strouhal number</td>
</tr>
<tr>
<td>$V_r$</td>
<td>Reduced velocity</td>
</tr>
<tr>
<td>A/D</td>
<td>Amplitude to Diameter ratio</td>
</tr>
<tr>
<td>Re</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>St</td>
<td>Strouhal number</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

1.1 Background and Motivation

The deep seafloor holds huge resource potential in the form of deposits of manganese nodules, cobalt rich crusts, polymetallic nodules and Seafloor Massive Sulfides (SMS). These deposits, which are found at depths of up to 6,000 m below the sea level, have attracted global interests in deep sea mining since 1960’s. Huge demand for minerals coupled with rapidly declining land-based deposits have prompted companies to venture into commercial scale deep sea mining. Many companies are now actively focusing on SMS deposits which contain appreciable amounts of copper and gold. These deposits are located at comparatively shallower depths of less than 2,000 m (Hoagland et al., 2010). Figure 1.1 shows the estimated resources of SMS and polymetallic nodules in oceanic waters around the globe. Though a lot of research and conceptual studies have been conducted in the area of deep sea mining, the industry is still in its early days. In 2011, Nautilus Minerals Inc., a deep sea mining company, have obtained mining license for an SMS deposit site located 30 km offshore Papua New Guinea. The exploration and development of this site, which is named Solwara-1, is being undertaken and the production is expected to start in the year 2018 (Berndt, 2015).

Many of the technologies used in deep sea mining have been adopted from the offshore
oil and gas industry. According to Chung and Tsurusaki (1994), the 1980’s saw significant technological developments in deep sea nodule-mining system and subsystems like hoisting systems, pipe deployment and retrieval systems and control systems. The major operations involved in deep sea mining are (1) exploration survey, (2) collection of nodules from the seabed, (3) hoisting the nodules to the surface vessel, (4) transportation to land and (5) processing of nodules either offshore or onshore. Hence, the mining system can be thought of as an integration of seafloor miner system, riser and lifting system, ship system and transportation system. An overview of the deep sea mining system is shown in Figure 1.2.

The Seafloor Production Tool (SPT) is a self-propelled vehicle, which moves on the seafloor and executes the task of excavating the minerals. These minerals are then collected by the SPT and hoisted to the production support vessel using the Riser and Lifting System (RALS). Further processing and transportation occurs at the surface.

The Riser and Lifting System (RALS) consists of a riser deployed from the production support vessel and a buffer equipment at the bottom end of the riser, which contains the pumping system for the nodules. The buffer is connected to the SPT using a flexible hose, which allows for the relative motion of the SPT with respect to the riser. This configuration means that the bottom end of the riser is free to move with very little resistance from the flexible hose. As the mining industry targets deeper and deeper waters, the length of the riser increases and many technical challenges arise as a result.
One of the key issues related to such a long riser is the Vortex-Induced Vibration (VIV), which is caused by the shedding of vortices around the riser in a current. Researches have confirmed that VIV can also occur to a flexible riser due to pure vessel motion (Wang et al., 2016b). Vessel motions, predominantly the surge and the sway, can create an equivalent oscillating current due to the relative motion of the riser in water. This vessel motion-induced VIV can cause similar fatigue damage to the riser as the ocean current-induced VIV (Wang et al., 2016b). The phenomenon of VIV in marine slender systems is still not fully comprehended and we have very little understanding of the VIV due to vessel motions. Although various numerical tools such as VIVANA and Shear7 are available to analyze the VIV of flexible systems, they are mostly suitable for ocean current induced cases and not for vessel motion-
induced cases. The present work attempts to bridge that gap and propose an empirical model for the prediction of vessel motion-induced VIV of a riser based on VIVANA software.

1.2 Objectives

The main objectives of this Master thesis study are as follows:

1. Formulate an empirical model for the prediction of vessel motion-induced VIV of a riser.
2. Validate the empirical model with the results from available riser model tests.
3. Validate the empirical model using full-scale data from actual field measurements of a drilling riser.
4. Use the validated empirical model to predict the VIV response due to vessel motions for an ultra-long deep sea mining riser.

1.3 Outline of the Thesis

The rest of the thesis is organized as follows:

Chapter 2 gives the theoretical background of the present work. A brief explanation on the phenomenon of VIV is provided and the key parameters related to VIV are defined.

In Chapter 3, the empirical model for the prediction of vessel motion-induced VIV is proposed. A brief explanation about the steps involved is presented.

In Chapter 4, the proposed model is validated against experimental results from small-scale riser model tests. The results from experiment is compared with the results from numerical analysis to validate the model.

In Chapter 5, the vessel motion-induced VIV is firstly identified in the full-scale measurements of a drilling riser and is then used for validation. The behaviour of a full-scale riser with
regard to vessel motion-induced VIV is investigated.

In Chapter 6, the validated empirical model is applied to an ultra-long deep sea mining riser. The VIV due to vessel motion is investigated and fatigue analysis is conducted. Current induced VIV is also studied and compared with vessel motion-induced VIV.

Chapter 7 summarizes the thesis work.
Chapter 2

Theory

2.1 Vortex Shedding and Vortex Induced Vibration

2.1.1 Vortex shedding

A cylindrical structure exposed to a uniform flow is shown in Figure 2.1.

![Cylinder exposed to uniform flow](image)

*Figure 2.1* Cylinder exposed to uniform flow (Goharzadeh and Molki, 2014)

When the fluid flows past the cylinder, a boundary layer is formed over its surface. This boundary layer is separated at the back end of the cylinder due to the adverse pressure gradient formed because of the diverging geometry of the cylinder cross-section. As a result, a shear layer, which separates itself from the surface, is formed. The fluid flowing over the
The cylinder surface contains a significant amount of vorticity. This vorticity is fed into the shear layer as well, which makes it to roll up into a vortex. Similarly, another vortex which rotates in the opposite direction, is formed from the other side of the cylinder. This pair of vortices are largely unstable and one of them will grow larger than the other. The larger vortex attracts the other one across the wake region behind the cylinder. Since both the vortices rotate in opposite directions, the approach of the smaller vortex of opposite vorticity will cut off further supply of vorticity to the larger one. At this instant the larger vortex is shed and moves downstream of the flow. When the vortex is shed, a new vortex will be formed at that side which is attracted towards the larger vortex on the other side. This leads to the shedding of vortex on the other side. This process continues and vortices are shed alternatively from both the sides (Sumer and Fredsøe, 2006).

The vortex shedding mechanism is depicted in Figure 2.2. The vortex B is drawn towards the larger vortex A. Once vortex A is shed, a new vortex C is formed there which in turn is drawn towards the vortex B.

![Figure 2.2 Mechanism of vortex shedding (Sumer and Fredsøe, 2006)](image)

### 2.1.2 Vortex induced vibration and lock-in

When slender marine structures like risers, pipeline free spans and mooring lines are exposed to a current flow, they may experience oscillations or vibrations. These vibrations are caused due to the shedding of vortices around the structure and when the shedding
frequency approaches the natural frequency of the structure. These are called Vortex Induced Vibrations (VIV).

A cylinder in still water will have many natural frequencies \( f_n \) based on the different modes of vibrations. When the cylinder is exposed to a flow, vortex shedding occurs with a shedding frequency \( f_v \). When this shedding frequency is equal to one of the natural frequencies of the cylinder, we have a resonance and the cylinder vibrates with a larger amplitude. The frequency of the response is equal to the other two frequencies. This is called as “lock-in”. Once we have a “lock-in”, the cylinder is said to experience VIV. It should be noted that in water, the added mass will vary and as a result the natural frequencies will also vary. Also, when the cylinder starts oscillating, the “effective diameter” will vary and as a result the vortex shedding frequency is not a constant. Hence, the response frequency of the cylinder will be a compromise between the natural frequency and vortex shedding frequency. VIV is a self-limiting process due to the hydrodynamic damping with increasing vibration amplitude, which means that if the amplitude exceeds a certain value, there will be no more transfer of energy from fluid to the cylinder but vice versa. The vibration along the direction of the flow is called as In-line (IL) VIV and the one perpendicular to the flow is called Cross-flow (CF) VIV. Generally, the amplitudes along the CF direction are much larger than the IL direction with IL frequency being twice that of CF frequency.

### 2.2 Governing Physical Parameters of VIV

#### 2.2.1 Reynolds number

The flow around a cylinder can be described using a non-dimensional quantity called Reynolds Number, which is defined as,

\[
Re = \frac{\text{Inertia Force}}{\text{Viscous Force}} = \frac{UD}{\nu} \tag{2.1}
\]

where,

D is the diameter of the cylinder (Characteristic length of the object)
U is the velocity of the flow

ν is the kinematic viscosity of the fluid (1 x 10^{-6} \text{ m}^2/\text{s} at 20^\circ \text{ C} for water)

When the Re is less than 5, no separation of the flow occurs behind the cylinder. As we increase the Re, a fixed pair of symmetric vortices are formed. This holds for the range 5 < Re < 40. When the Re is increased above 40, we get a laminar flow with alternate shedding of vortices. As the flow reaches the regime 300 < Re < 3 \times 10^5, known as sub-critical flow region, the wake is fully turbulent with alternate shedding of vortex. Many of the realistic flow problems falls in this region. The vortex shedding patterns for various range of Re values are shown in Figure 2.3.

![Vortex patterns behind a cylinder for various Re regimes (Sumer and Fredsøe, 2006)](image)

**Figure 2.3** Vortex patterns behind a cylinder for various Re regimes (Sumer and Fredsøe, 2006)

### 2.2.2 Vortex shedding frequency

The frequency of the vortex shedding of a fixed cylinder (i.e. shedding of a pair of vortices) is governed by the non-dimensional number known as Strouhal number. The Strouhal number
is defined as,

$$St = \frac{f_v D}{U} \quad (2.2)$$

where,

$f_v$ is the vortex shedding frequency of a fixed cylinder subjected to steady flow.

Figure 2.4 shows the relationship between the Strouhal number and Reynolds number for a smooth cylinder. It can be seen that the Strouhal number remains a constant with a value of 0.2 throughout the sub-critical range. The Strouhal number is also a function of the roughness of the cylinder.
2.2.3 Mass ratio

Mass ratio is defined as the ratio of mass of the cylinder per unit length to the mass of the displaced fluid per unit length.

\[ M = \frac{4m}{\rho \pi D^2} \]  

(2.3)

where,

- \( m \) is the mass of the cylinder per unit length
- \( \rho \) is the fluid density

Mass ratio is a parameter which indicates the tendency of the structure to experience flow induced vibrations. Higher the mass ratio, lower will be the vibrations due to flow.

2.2.4 Reduced velocity

The non-dimensional parameter reduced velocity is defined as,

\[ V_r = \frac{U}{f_i D} \]  

(2.4)

where,

- \( f_i \) is the natural frequency of the cylinder.

A reduced velocity can be found for each natural frequency of the cylinder. When a cylinder vibrates with a frequency \( f_i \) in a flow of constant velocity \( U \), then \( V_r \) is the ratio of the wavelength of the flow trajectory \( (U \times 1/f_i) \) to the diameter of the cylinder (\( D \)) (Sumer and Fredsøe, 2006), i.e. in cross flow vibrations, it represents the travelling length during a vibration period w.r.t the diameter. The lock-in phenomenon can be explained using reduced velocity. From Figure 2.5, which is for a mass ratio of 5.3, it can be seen that the vibration starts to occur with large amplitudes when the ratio of vortex shedding frequency and natural frequency (y-axis) reaches 1 at around \( V_r = 5 \). When \( V_r \) is in the range of 6-8, the shedding frequency departs from the Strouhal law and follows the natural frequency of the system. This range is the lock-in range corresponding to the non-dimensional frequency region where there is positive \( C_{LV} \) (lift coefficient in phase with
CF velocity) and larger amplitudes of vibration. After that, the vortex shedding frequency follows the Strouhal law.

2.2.5 **Keulegan-Carpenter (KC) number**

When a cylinder is subjected to an oscillatory flow, Reynolds number is not the only parameter that describes the flow. A parameter called Keulegan-Carpenter (KC) number also comes into picture. The KC number is defined as (Sumer and Fredsøe, 2006),
\[ KC = \frac{U_m T_w}{D} \]  

(2.5)

where,

- \( U_m \) is the maximum velocity
- \( T_w \) is the period of the oscillatory flow

KC number indicate the ratio of drag force to the inertia force on a cylinder.

In case of a harmonic flow,

\[ U_m = \frac{2\pi A}{T_w} \]  

(2.6)

where \( A \) is the amplitude of the motion

Hence, the KC number can be written as,

\[ KC = \frac{2\pi A}{D} \]  

(2.7)

This equation describes the distance covered by a water particle, under oscillatory flow, relative to the width of the cylinder. Large KC number indicates that the particles travel a longer distance relative to the width of the cylinder and results in separation from the surface and hence vortex shedding. Smaller KC number indicates shorter distance travelled and it is possible that the separation may not occur in this case (Sumer and Fredsøe, 2006).

Sumer and Fredsøe (2006) also gives the relation between VIV response frequency \( f_{\text{resp}} \) and frequency of the imposed motion of the cylinder \( f_{\text{im}} \) for different KC ranges based on the results from flexibly mounted rigid cylinder tests in oscillatory flows.

\[ N = \frac{f_{\text{resp}}}{f_{\text{im}}} = \begin{cases} 
2; & 7 < KC < 15 \\
3; & 15 < KC < 24 \\
4; & 24 < KC < 32 \\
... 
\end{cases} \]  

(2.8)
According to Sumer and Fredsøe (2006) and Fernandes et al. (2014), $N$ also depends on the range of $V_r$ and Re for a rigid cylinder. In case of a flexible cylinder, it is more KC dominant. The local response at a point is influenced by the response from nearby points.

### 2.3 Semi-empirical VIV Prediction Method

Standard numerical tools for the prediction of VIV use empirical hydrodynamic force models in combination with finite element method for the structure. VIVANA is such a program used for the prediction of VIV of slender marine structures subjected to a current flow. In VIVANA, the concurrent or space sharing assumption is followed in which all the possible response frequencies are allocated various sections of the structure (MARINTEK, 2016). Each response frequency will have its own zone where it is excited due to the vortex shedding at that zone. This zone is defined based on the dimensionless parameter called non-dimensional frequency, which is defined as:

$$
\hat{f}_i(z) = \frac{f_{osc,i} D(z)}{U(z)}
$$

where $f_{osc,i}$ is the response frequency.

Figure 2.6 explains the allocation of the excitation zones along the length of the structure subjected to a shear current flow.

It is to be noted that an interval of 0.125-0.3 for $\hat{f}$ is used to define the excitation zones. This interval is based on the findings from the experiments conducted on rigid cylinders by Gopalkrishnan (1993). There may be cases of overlap of many response frequencies at a certain point on the structure. In such a case, VIVANA uses an excitation parameter based on energy considerations to prioritize among the overlapping frequencies. This parameter is defined as (MARINTEK, 2016),

$$
E_i = \int_{L_{e,i}} U^3(z)D^2(z) \left( \frac{A}{D} \right) \left( \frac{A}{D} \right)_{C_e=0} ds
$$

(2.10)
Figure 2.6 Excitation zones along the structure exposed to a shear current (MARINTEK, 2016)

where $L_{e,i}$ is the length of the excitation zone and $\left(\frac{A}{D}\right)_{C_e=0}$ is the non-dimensional amplitude where the excitation coefficient shifts from positive to negative value.

Figure 2.7 Excitation zones along the structure without overlapping frequencies (MARINTEK, 2016)
Finally, VIVANA allocates a unique zone for each response frequency candidate as shown in Figure 2.7. The final response of the structure will be considering all the excitation frequencies along the structure.

Once the VIV frequency is obtained and dominant mode identified, then the response of the structure is evaluated using the built-in hydrodynamic force model of VIVANA.
Chapter 3

Empirical Model for Prediction of Vessel Motion-induced VIV

3.1 Introduction

The vessel motion-induced VIV was first reported in STRIDE, a Joint Industry Project focused on compliant risers (Willis and Thethi, 1999). This was further studied by Gonzalez (2001), Cunff et al. (2005) and Rateiro et al. (2013). Many studies were later conducted using model tests to study the VIV of a free-hanging riser under oscillatory motion. Kwon et al. (2015) conducted experiments on a riser model under oscillatory motion for KC numbers as low as 2.24. Wang et al. (2016a) did similar study on an 8 m long free-hanging riser subjected to pure vessel motion. The equivalent current velocity, effect of KC number and VIV responses were investigated. The CF VIV was observed for a KC number as low as 12.

The effect of low KC numbers on VIV was further studied by Vedeld et al. (2016) for free-span pipelines under waves. At low KC numbers (KC<40), the oscillations are no longer governed by the dimensionless parameters like reduced velocity, but by the ratio N of dominating frequency of the lift force $f_L$ (or dominating response frequency $f_{\text{resp}}$) and the wave frequency
$f_w$ (or the frequency of imposed motion $f_{im}$), i.e.,

$$N = \frac{f_L}{f_w} = \frac{f_{resp}}{f_{im}}$$

(3.1)

The values of $N$ for various KC number ranges are found through experiments by Williamson (1985). It was observed that the value of $N$ increases step-wise with KC number. $N$ is found to increase by 1 with an increase of 8 in KC number. Table 3.1 shows values of $N$ for various KC regimes.

**Table 3.1** Value of the ratio $N$ for various KC regimes (Williamson, 1985)

<table>
<thead>
<tr>
<th>KC number range</th>
<th>$N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$7 &lt; KC &lt; 15$</td>
<td>2</td>
</tr>
<tr>
<td>$15 &lt; KC &lt; 24$</td>
<td>3</td>
</tr>
<tr>
<td>$24 &lt; KC &lt; 32$</td>
<td>4</td>
</tr>
<tr>
<td>$32 &lt; KC &lt; 40$</td>
<td>5</td>
</tr>
</tbody>
</table>

Similar observations were made by Wang et al. (2016c) when they conducted a model test on a free-hanging Water Intake Riser (WIR) under vessel motions. The frequencies observed during this study are presented in Table 3.2. At low KC numbers, the observed dominant response frequency does not match with the shedding frequency estimated from Strouhal relation using $St=0.2$, but follows an integral relationship with the frequency of motion.

**Table 3.2** Frequency information from experiment (Wang et al., 2016c)

<table>
<thead>
<tr>
<th>Case No.</th>
<th>$KC_{top}$</th>
<th>Frequency of motion $f_{im}$ (Hz)</th>
<th>Dominant response frequency $f_{resp}$ (Hz)</th>
<th>Estimated shedding frequency $f_{stmax}$ (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25.5</td>
<td>0.14</td>
<td>0.28</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>22.5</td>
<td>0.21</td>
<td>0.42</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>9.9</td>
<td>0.32</td>
<td>0.32</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>5.33</td>
<td>0.42</td>
<td>0.42</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>2.28</td>
<td>0.63</td>
<td>0.63</td>
<td>1</td>
</tr>
</tbody>
</table>

In this chapter, an empirical model to predict the vessel motion-induced VIV of a marine riser under low KC numbers using VIVANA software is proposed. Vessel motion can generate
an equivalent oscillatory flow which is experienced by the riser. As mentioned before, the important non-dimensional parameter that govern an oscillatory flow is KC number. For low KC number cases (<40), the response frequency is not in agreement with the shedding frequency estimated from Strouhal relation, but follows an integral relation with the imposed motion frequency.

### 3.2 Proposed Empirical Prediction Model

#### 3.2.1 Equivalent current profile

Current Profile is the major input for VIV analysis. VIVANA allows a two dimensional current profile, i.e. variation of current velocity with depth, to be given as the input. When considering vessel motion-induced cases, it is necessary to convert the motion of the vessel and the riser into an *equivalent current profile*. Equivalent current is the current that the riser “sees” due to its relative motion in water. The VIV of the riser due to this current is then analysed in VIVANA to get the responses.

![Illustration of velocities along the riser](image)

*Figure 3.1 Illustration of velocities along the riser*
As seen from the illustration in Figure 3.1, the motion of the riser in water over time provides us with velocity time series at each node. An equivalent current profile has to be then derived from these velocities.

Following are the various methods of generating equivalent current profile from the velocity time series:

1. Equivalent Current Profile 1: Here the maximum velocity at each node is taken and a current profile is generated based on it. This is illustrated in Figure 3.2.

\[ U_e(z) = \max(U(z, t)) \]  

2. Equivalent Current Profile 2: Here the standard deviation of the velocity time series is multiplied by \( \sqrt{2} \) in order to get the representative maximum at each node. If the velocity time series is harmonic, then this profile will be similar to Equivalent Current Profile 1. This method can be used to estimate the equivalent current profile in case of irregular vessel motions (Wang et al., 2016b). This method is shown in Figure 3.3.

\[ U_e(z) = \sqrt{2} \times \sigma_U(z, t) \]
3. Equivalent Current Profile 3: A number of velocity snapshots along the length of the riser, each at a particular instant of time, are taken and these snapshots are used as the equivalent current profiles. The VIV responses for each profile is investigated and the final response is taken as the average of all of them.

$$\left( \frac{A}{D} \right) (z) = \frac{1}{N} \sum_{i=1}^{N} \left( \frac{A}{D} \right)_{i} (z)$$ (3.4)

where $N$ is the no. of velocity snapshots.

Equation 3.4 shows how the response amplitude is averaged. Stress and fatigue damage can be calculated in similar way. The profile is illustrated in Figure 3.4. This method of multiple time windows can be said to be the best approximation of analysis with time varying velocity profiles and has been demonstrated by Wu et al. (2015) when investigating the VIV response of a steel catenary riser under heave induced motion.

The first two methods are mostly suitable for the low KC number cases, where VIV is more consistent in time in terms of response frequency. For large KC number cases, VIV is more time-varying in terms of response frequency, mode and amplitude. Hence, use of multiple time windows and then averaging them as an approximation comes into significance.
3.2.2 Representative KC number

A riser moving in water will have a varying KC number distribution along its length. In most cases, the maximum occurs at the top of the riser due to the vessel motion and the rest of the riser experience a value lower than the one at the top. It is necessary to define a representative KC number that best describes the riser motion. This value will be used to obtain the value of $N$. Figure 3.5 shows an illustration of a typical KC number distribution. It can be seen that the maximum value is not a representation of the KC distribution. Hence, in this model we define the representative KC number as the midpoint of the distribution (midpoint value between max. and min. of the distribution). This is also illustrated in the figure. It is to be noted that this definition will be necessary only if the variation in KC along the length is large. In case of small variations, the representative KC range can be judged easily from the distribution.
3.2.3 Response frequency model for low KC number cases

As discussed before, when the KC number is less than 40, the VIV response is no longer governed by the Strouhal relationship. There exists an integral relationship between response frequency and imposed motion frequency (Vedeld et al., 2016). As a result, for the cases with low KC numbers, the value of $N$ from the Table 3.1 is used to estimate the response frequency.

\[ f_{\text{resp}} = N \times f_{\text{im}} \]  \hspace{1cm} (3.5)

At lock-in we have $f_v = f_{\text{resp}}$

This can be applied to the Strouhal relation to get the equivalent Strouhal number that causes this $f_v$

\[ St^* = \frac{f_v D}{U} \]  \hspace{1cm} (3.6)

This equivalent Strouhal number $St^*$ is to be used in VIVANA to predict the VIV. This is based on the empirical model that at low KC numbers we can predict the response frequency based on the imposed motion frequency and the KC number range. Here $U$ is the ”dominant” velocity that causes the dominant frequency along the riser. In many cases it is the maximum
velocity, but it can also be the average velocity or any value in between and this depends on
the distribution of the equivalent current profile.

A step-by-step approach to predict the vessel motion-induced VIV at low KC numbers is
given below. This process is illustrated in Figure 3.6 using a flowchart. The empirical model
is also described in Wang et al. (2017).

Step 1: Calculate the riser response based on the vessel motions. Obtain the velocity
distribution \( U(z,t) \) and the KC number distribution \( KC(z) \) along the riser length.

Step 2: Generate the equivalent current profile \( U_e(z) \) based on the methods described
previously. In case of a harmonic motion, equivalent current profile 1 can be used
(refer Equation 3.2). Equivalent current profile 2, proposed by Wang et al. (2016b),
is a more generalized method and is suitable to irregular motions as well (refer
Equation 3.3).

Step 3: Choose the value of \( N \) from Table 3.1 based on the KC number distribution along
the riser and calculate \( f_{\text{resp}} \) from Equation 3.5.

Step 4: An initial equivalent Strouhal number \( St^* \) is then calculated from Equation 3.6 using
the maximum velocity as \( U \).

Step 5: Using \( U_e(z) \) and \( St^* \) as inputs, the dominant response frequency, \( f_{\text{dom}} \) is identified
from VIVANA. Further, the value of \( St^* \) is updated so that \( f_{\text{dom}} \) from VIVANA is
approx. equal to \( f_{\text{resp}} \) calculated from Step 3.

The methodology used by VIVANA to determine the response frequencies is described in
Chapter 2 section 2.3. In our response frequency model, we define the dominant response
frequency \( f_{\text{dom}} \) as the frequency excited along the major length of the riser. The final response
will be heavily influenced by this frequency.
1. Calculate riser responses from vessel motion \( U(z,t), KC(z) \)

2. Generate equivalent current profile \( U_e \)

3. Select \( N \) based on \( KC(z) \)
   \[ f_{resp} = N \times f_{im} \]

4. Calculate \( St^* = \frac{f_{resp} D}{U} \) (init. \( U = U_{max} \))

5. Identify dominant response frequency \( f_{dom} \) from VIVANA

\[ \text{Is } f_{dom} \approx f_{resp} \]

no \quad Update \( St^* \)

yes \quad Stop

**Figure 3.6** Flowchart illustrating the empirical frequency response model

### 3.2.4 VIV prediction for high KC number cases

In case of high KC numbers, i.e. \( KC > 40 \), the response frequency is influenced by the Strouhal relation and hence the empirical model need not necessarily be used. However, the N-KC relationship exists for high KC number cases as well and hence the model can be considered
as generic. Whereas in low KC number cases the Strouhal relation would not predict the actual response frequency and the model should be used, in high KC number cases either of them would provide the response. The value of N can be incremented by 1 for every increase of 8 in KC number (Sumer and Fredsøe, 2006). Hence, the Table 3.1 can be expanded to accommodate higher values of KC as well.

3.3 Vibration Amplitudes for Irregular Motions

The vessel motion that causes the VIV can be both regular and irregular. Although in realistic scenarios the motions are irregular, experimental studies mainly concern with regular motions for the purpose of fundamental studies. In case of irregular motions, the amplitudes of vibration from the numerical analysis is to be reduced by 60% (Sumer and Fredsøe, 2006, p. 441-442). According to Sumer and Fredsøe (2006), for cases with irregular waves, ”the maximum amplitudes are reduced by about 60% with respect to the values experienced in the case of regular waves”. Hence, it is imperative to reduce the amplitude of vibration obtained from VIVANA by 60% while considering irregular motions.
Chapter 4

Empirical Model Validation: Against Model Test Results

4.1 Introduction

An empirical model to predict the VIV due to vessel motion was described in the previous chapter. In order to validate the model, a validation study is conducted. Two experimental models of free-hanging risers under vessel motions are validated here. The experimental setups are modelled in RIFLEX and the VIV is analysed using VIVANA. The main target of the validation is to recreate the riser model and be able to predict the response frequency with good accuracy using the proposed empirical model.

4.2 Methodology

The riser configuration is modelled in RIFLEX based on the riser properties. A modal analysis of the riser is then conducted. The natural frequencies of the riser in still water and the mode shapes are obtained. The comparison of the natural frequencies from the modal analysis and the experimental results is a good way to check whether the modelled configuration is similar to the actual test riser.
The riser is then subjected to regular harmonic vessel motions of the form \( x = A \sin \omega t \), where \( A \) is the amplitude of the motion and \( \omega \) is the frequency in rad/s.

The dynamic behavior of the riser under the vessel motion is analyzed over a period of time (preferably \( 20 \times \) period of motion) to obtain the steady state responses. These responses are used to compute the velocities at each node of the riser. Once the velocities are known, equivalent current profile is generated. The KC number is then calculated from Equation 2.7 and the distribution along the riser is obtained. The maximum amplitude at each node is used in the equation to calculate the KC number. The value of \( N \) is chosen from Table 3.1 based on the KC range. Finally, from Equation 3.1 \( f_{\text{resp}} \) is estimated and equivalent Strouhal number \( St^* \) is calculated. This, along with equivalent current profile, is the input for VIVANA analysis.

Two validation studies are performed using the data from the model tests of a free-hanging riser under vessel motion conducted by Wang et al. (2016c) and Wang et al. (2016a) respectively. These are simpler small scale models of a free-hanging riser and are subjected to simple harmonic vessel motions.

### 4.3 Validation Based on Water Intake Riser Model Test

This study is based on the results from the experiment conducted by Wang et al. (2016c). The aim of the experiment was to study the dynamic behaviour of a WIR prototype under vessel motion. A scaled model of the riser, made of HDPE (High Density Polyethylene), was tested in an ocean basin and the top of the riser was excited with various harmonic motions. The dimensions and properties of the model riser are given in Table 4.1.

The main measured parameter in the experiment is the strain values measured at 16 points along the riser. 4 FBG (Fiber Brag Grating) strain sensors were placed around the cross-section at each measuring point (Wang et al., 2016c). The riser model was subjected to motions of various amplitudes and time periods of which one is selected for the validation.
Table 4.1 Properties of model riser (Wang et al., 2016c)

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>35.66</td>
<td>m</td>
</tr>
<tr>
<td>Outer diameter</td>
<td>0.165</td>
<td>m</td>
</tr>
<tr>
<td>Inner diameter</td>
<td>0.15</td>
<td>m</td>
</tr>
<tr>
<td>Cross-sectional area, A</td>
<td>0.0037</td>
<td>m²</td>
</tr>
<tr>
<td>Modulus of elasticity, E</td>
<td>$8.9 \times 10^8$</td>
<td>N/m²</td>
</tr>
<tr>
<td>Bending stiffness, EI</td>
<td>12022</td>
<td>Nm²</td>
</tr>
<tr>
<td>Tensioning stiffness, EA</td>
<td>$3.3 \times 10^6$</td>
<td>N</td>
</tr>
<tr>
<td>Mass/unit length in air</td>
<td>3.61</td>
<td>kg/m</td>
</tr>
<tr>
<td>Mass of buffer in air</td>
<td>13.53</td>
<td>kg</td>
</tr>
</tbody>
</table>

The amplitude and time period of the oscillation are summarized in Table 4.2.

Table 4.2 Riser motions (Wang et al., 2016c)

<table>
<thead>
<tr>
<th>Amp (m)</th>
<th>T (s)</th>
<th>f (Hz)</th>
<th>$KC_{top}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.67</td>
<td>7.13</td>
<td>0.14</td>
<td>25.5</td>
</tr>
</tbody>
</table>

4.3.1 Results and discussion

The eigen frequencies of the riser in still water are calculated based on the riser properties. The eigen frequencies for the first 10 modes are shown in Figure 4.1. The normalized mode shapes for the first 5 modes are presented in Figure 4.2.
Figure 4.1 Eigen modes and Eigen frequencies of the WIR model

The equivalent current profile generated for the case is shown in Figure 4.3. In this case Equation 3.3 is used to obtain the equivalent current profile.
The KC number distribution is presented in Figure 4.4. The maximum value of KC occurs at the top part of the riser and the major portion of the riser experience a much lower KC number. The representative KC number which best describes the KC distribution is found to be in the range of 7-15. According to Sumer and Fredsøe (2006), in this case the integral ratio N of response frequency and imposed frequency of the riser is to be equal to 2, i.e., the dominant response frequency expected for the riser is twice the frequency of top motion.
As mentioned in the previous chapter, the maximum velocity is used to calculate an initial $St^*$. This is used in VIVANA to analyze the VIV. The dominant response frequency from the VIVANA is then used to update the value of $St^*$. In this case, the value of $St^*$ which gives $f_{dom} = f_{resp}$ is equal to 0.36.

Figure 4.5 shows the excitation frequencies along the length of the riser obtained from VIVANA analysis. It can be seen that the dominant response frequency along the riser is 0.28 Hz, which is twice the frequency of the imposed motion (0.14 Hz). The response plots from the experiment also point to a frequency of the same value and this corresponds to 4th mode of the riser (refer Figure 4.6).
The RMS value of strain measurements from the experiment is compared with that obtained from the analysis and is presented in Figure 4.7. It can be seen that the mode from the analysis agrees well with the mode from the experiments. The maximum strain value obtained is slightly higher and hence is a conservative prediction.

Figure 4.6 Response frequency along the riser from experiment for WIR (Wang et al., 2016c)

Figure 4.7 Comparison of RMS strain values for WIR
The RMS A/D is compared in Figure 4.8. The mode shape agrees well with the experimental results. The values are in good agreement for the one-third of the riser.

![Figure 4.8 Comparison of RMS A/D for WIR](image)

The difference in the strain values between analysis and measurements may be due to the difference in relative structural damping of the actual model and the numerical model. Since the data was unavailable, 5% relative structural damping was assumed based on the findings by Munson et al. (2012) for HDPE (High Density Polyethylene) pipe.

### 4.4 Validation Based on Free-Hanging Riser Model Test

The empirical model is validated based on the results from the experiments of Wang et al. (2016a). A model test of an 8 m long free-hanging riser was conducted for pure vessel motions under different ranges of KC numbers. The properties of the riser are summarized in Table 4.3.

It is to be noted that here the initial 1.38 m of the riser is kept above the water level. In this experiment also, the responses were measured using the strain gauges. A total of 64 FBG
Table 4.3 Properties of model riser (Wang et al., 2016a)

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>8</td>
<td>m</td>
</tr>
<tr>
<td>Outer diameter</td>
<td>0.029</td>
<td>m</td>
</tr>
<tr>
<td>Inner diameter</td>
<td>0.019</td>
<td>m</td>
</tr>
<tr>
<td>Cross-sectional area, A</td>
<td>0.00037</td>
<td>m²</td>
</tr>
<tr>
<td>Modulus of elasticity, E</td>
<td>$1.42 \times 10^9$</td>
<td>N/m²</td>
</tr>
<tr>
<td>Bending stiffness, EI</td>
<td>50.8</td>
<td>Nm²</td>
</tr>
<tr>
<td>Tensioning stiffness, EA</td>
<td>$5.3 \times 10^5$</td>
<td>N</td>
</tr>
<tr>
<td>Mass/unit length in air</td>
<td>1.61</td>
<td>kg/m</td>
</tr>
<tr>
<td>Mass of buffer in air</td>
<td>9</td>
<td>kg</td>
</tr>
</tbody>
</table>

Sensors were used in this case. There were 16 measuring points along the riser and at each point 4 sensors were placed symmetrically along the cross-section (Wang et al., 2016a). The amplitudes and periods of riser motions selected for the validation are given in Table 4.4.

Table 4.4 Riser motions (Wang et al., 2016a)

<table>
<thead>
<tr>
<th>Case</th>
<th>Amp (m)</th>
<th>T (s)</th>
<th>f (Hz)</th>
<th>$KC_{top}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.051</td>
<td>1.1</td>
<td>0.91</td>
<td>11</td>
</tr>
<tr>
<td>2</td>
<td>0.28</td>
<td>5.52</td>
<td>0.18</td>
<td>61</td>
</tr>
</tbody>
</table>

4.4.1 Results and discussion

The results from the validation study are presented below. The eigen frequencies of the riser in still water for the first 10 modes are presented in Figure 4.9. Figure 4.10 shows the normalized mode shapes for the first 5 modes.
4.4.1.1 Case 1

The top KC number for this case is 11. The equivalent current profile is as shown in Figure 4.11. It can be seen that the maximum velocity occurs not at the top, but at a point 4.5 m from the top.
A look at the KC number distribution from Figure 4.12 confirms that the major part of the riser experiences a KC higher than 8. Hence, we can choose N=2 for this case, i.e., the dominant response is expected to be at twice the frequency of imposed motion.

Figure 4.13 shows the frequency plot of the CF response from the experiment. It can be seen that the responses are with a frequency of 1.8 Hz, which is twice that of the frequency
of imposed motion. Figure 4.14 shows the excitation frequencies from the VIVANA analysis using the proposed empirical model. The value of $St^*$ used here is 0.174. The dominant response frequency from VIVANA is also 1.8 Hz and it is good agreement with the response frequency from the experiment. This frequency corresponds to the 4th eigen mode of the riser.

**Figure 4.13** Response freq. along riser for Case 1 from experiment (Wang et al., 2016a)

**Figure 4.14** Excitation frequencies from VIVANA for Case 1
Figure 4.15 shows the strains obtained from the analysis. This can be compared with the maximum strain values from the time varying strain responses from the experiment presented in Figure 4.16.

![Figure 4.15 Strain values for Case 1](image)

It can be seen that the maximum value of strain at the midpoint of the riser (Sensor no. 10) is around $0.5 \times 10^{-4}$ to $1 \times 10^{-4}$. The value obtained from analysis is higher than the one from experiments, but it is evident that the frequency and the mode of vibration matches well with experiment data.

![Figure 4.16 Time varying strain from experiment for Case 1 (Wang et al., 2016a)](image)
### 4.4.1.2 Case 2

The top KC number in this case is 61. Even though the dominant response frequency is not necessarily influenced by the imposed motion as in the case of low KC numbers, the proposed empirical model can still be applied to the case. The equivalent current profile is illustrated in Figure 4.17.

![Figure 4.17 Equivalent current profile for Case 2](image)

The KC number distribution is shown in Figure 4.18. It is evident that the value of KC changes drastically along the length of the riser. In order to predict the response frequency using the empirical model, it is important to define a particular representative KC number that best describes the case. This KC is in turn used to select the value of N. In the present case, we use the method described in section 3.2.2 to describe the representative KC. Hence, in this case the representative KC number is taken as the midpoint of the distribution and is equal to 78. It is to be noted that the same applies to Case 1 as well, but since the variation in values is not as large as in this case, we could easily judge the representative KC.
According to Sumer and Fredsøe (2006), the value of N is increased by 1 with an increase of 8 in KC number. Therefore, this case should belong to a KC regime with N=10. Figure 4.19 shows the frequency of CF response from the experiment. The dominant response is with a frequency of about 1.8 Hz. Here, the frequency of imposed motion is 0.18 Hz, hence as per the empirical model the response frequency should be 1.8 Hz.
Figure 4.20 shows the excitation frequencies along the riser from VIVANA analysis. It can be seen that the frequency predicted using the model agrees well with that from the experiment. Also, the value of $St^*$ used here is 0.18. This value of $St^*$ is similar to the actual value of $St$ for this case based on the Re value and surface roughness. Hence, even if the proposed model is not followed here, we could get similar response frequency for this case. This proves our theory that for higher KC numbers, the proposed model will still be applicable even though not necessarily required.

![Figure 4.20 Excitation frequencies from VIVANA for Case 2](image)

From Figure 4.19, it can be seen that more than one mode participate in the response in this case. One equivalent current profile will not be able to predict all the responses. As such in this case the multiple time window profile proposed by Wu et al. (2015) (Equivalent Current Profile 3) comes into significance.

The maximum strains along the riser from analysis is plotted in Figure 4.21. Figure 4.22 shows the time varying strains from the experiment. The maximum value of strain from the experimental data is in the range of $1 \times 10^{-4}$ to $2 \times 10^{-4}$. The values obtained from analysis agree well in this regard.
4.5 Discussion

The model validation studies provided good results considering the various constraints like correctness of the input data, experimental and modelling errors, etc. The main aim of validation studies was to prove the feasibility and accuracy of the proposed response frequency prediction model for vessel motion-induced VIV at low KC number cases. The model was able to successfully predict the dominant response frequency of all the cases. A case of KC
number higher than 40 was considered and the model could predict the response for that particular case. This also proves that the model is generic in character and can be applied regardless of the KC number range. The model has its significance in lower KC number range since the Strouhal relation, using constant Strouhal number as 0.18, fails to predict the VIV response in that range.
Chapter 5

Empirical Model Validation: Against Full-scale Measurements

5.1 Introduction

In the previous chapter, model validation using small scale model test data was discussed. Before extending the application of the empirical model to an ultra-long riser, it is necessary to investigate how the model works in case of an actual long riser. In this chapter, the empirical model is applied to an actual full-scale drilling riser and the results are compared with the field measurements. These measurements of the full-scale drilling riser were performed 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 Center for Ocean Engineering, MIT for the purpose of calibration and benchmarking of VIV softwares (BP and 2H Offshore, 2008) and is publicly accessible. The main parameter in the data set is the accelerations measured by accelerometers at various points along the length of the riser. One of the main issues pertaining to the application of the empirical model to the riser is the identification of the vessel motion-induced VIV from the acceleration measurements. Absence of any details regarding the vessel or the wave data makes this task even more difficult. Nevertheless, a conscious effort has been made to identify vessel motion-induced
VIV from available data and apply the empirical model to the riser. As has been the case in the previous validation study, the goal is not to obtain the exact amplitudes of vibration or stresses, but to predict the response frequency and the dominant mode with reasonable accuracy. It is to be noted that the full-scale measurements corresponds to the cases with irregular vessel motions.

5.2 Full-scale Data Information

The dataset contains the following:

1. Riser configuration, dimensions and riser weight.
2. Tension and mud weight data.
3. Current data at the location.
4. Acceleration data from accelerometers at various points on the riser.

5.2.1 Riser configuration

Two wells were drilled during the drilling period. The configuration of the riser during drilling of well-1 is illustrated in Figure 5.1. The measurement loggers are named as S01, S02, ..., S13 with S01 situated on the drill floor. Their locations are indicated by the red squares in the figure. 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 minimum possible number of loggers. An optimum placement of loggers should capture atleast the quarter wavelength of the lowest mode expected (Natarajan et al., 2006).

The riser material is steel with a density of 7850 kg/m$^3$ and modulus of elasticity of $2.07 \times 10^{11}$ N/m$^2$. The outer diameter is 21 inches.
Figure 5.1 Configuration of the drilling riser (BP and 2H Offshore, 2008)
Table 5.1 shows the distances from the drill floor at which the loggers are located on the riser.

<table>
<thead>
<tr>
<th>Logger ID</th>
<th>Distance from the drill floor (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S01</td>
<td>0</td>
</tr>
<tr>
<td>S02</td>
<td>775</td>
</tr>
<tr>
<td>S03</td>
<td>798</td>
</tr>
<tr>
<td>S04</td>
<td>1436</td>
</tr>
<tr>
<td>S05</td>
<td>1458.8</td>
</tr>
<tr>
<td>S06</td>
<td>1481.7</td>
</tr>
<tr>
<td>S07</td>
<td>1504.5</td>
</tr>
<tr>
<td>S08</td>
<td>1550.2</td>
</tr>
<tr>
<td>S09</td>
<td>1596</td>
</tr>
<tr>
<td>S10</td>
<td>1641.7</td>
</tr>
<tr>
<td>S11</td>
<td>1687.4</td>
</tr>
<tr>
<td>S12</td>
<td>1733</td>
</tr>
<tr>
<td>S13</td>
<td>1739</td>
</tr>
</tbody>
</table>

Figure 5.2 shows the top tension of the riser and the density of mud used during the drilling period.

**Figure 5.2** Riser tension and mud density (BP and 2H Offshore, 2008)
5.2.2 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. A 300 kHz horizontal ADCP measures the current at 36 m below MSL and a downward looking 38 kHz ADCP covers depths from 72 m to 1128 m below MSL. An upward looking 75 kHz ADCP measures current between 26 m and 586 m above the seabed. The current is sampled at every 10 minutes and averaged (BP and 2H Offshore, 2008). A constant density of 1025 kg/m$^3$ is assumed for the sea water.

5.2.3 Instrumentation

The instrumentation consists of 13 standalone loggers. One of the loggers is located on the drill floor and measures the vessel acceleration. The other loggers are placed at various locations on the riser. The logger contains the sensors, batteries, memory card and all the associated electronics encased within a cylindrical casing (BP and 2H Offshore, 2008). The loggers are then strapped to the structure. Typically, motion sensors in the logger are made of tri-axial accelerometers and tri-planar angular rate sensors (Thethi et al., 2005), but the angular rate sensors are not active in this experiment.

5.2.4 Accelerations and events

The accelerometer measures the acceleration at the location in three axes. The data is measured continuously for a duration of 15 minutes at each 2 hour interval. This limited time of measurement is because of the fact that the loggers have a limited battery life and it has to be conserved for the whole drilling period. The sampling frequency is 10 Hz. Each 15 minute period of measurement is termed as an event. There are a total of 1078 events captured during the drilling period. These events are spread over 3 operational cases - (1) drilling of well-1, (2) hang-off and transport and (3) drilling of well-2.
5.2.5 Limitations

Following are some of the known limitations of the measurements:

1. The accelerometers are standalone and exact time synchronization may not be possible.
2. The alignment of logger X and Y axes with the global X and Y axes is not guaranteed.
3. Some of current data are missing due to the unavailability of ADCPs during that period.
4. The accuracy of accelerometers at low frequencies is not guaranteed.
5. Most of the acceleration data are polluted and of poor quality. Poor quality data can provide misleading results. Figure 5.3 shows the time series of acceleration at a logger for a particular event. It can be seen that the acceleration readings appear to be truncated and is not continuous.

Figure 5.3 (a) Acceleration time series at a particular sensor showing poor quality data (b) Zoomed in picture showing discontinuity in data

One of the reasons for this may be that the accelerometers are of low precision and hence the adjacent readings appear to be the same. In the present analysis, data of poor
quality was identified and discarded. The criterion used here is that cases with similar adjacent readings amounting to more than 15% of the total readings are classified to be poor quality data.

Figure 5.4 shows an example of the acceleration time series which can be considered as acceptable for the analysis.

![Figure 5.4 Acceptable acceleration time series at a particular sensor](image)

### 5.3 Data Analysis

The accelerations in X, Y and Z axes are available for all the events during the drilling period. Along with these, the current speed and direction are also available. The main task is to identify current-induced VIV and vessel motion-induced VIV from these data for the various events.

The VIV and the response frequency can be identified by performing a spectral analysis of the accelerations or displacements at each logger location. The peak frequencies of the spectrum, which fall within the VIV frequency range, across all loggers can be identified and correlated. The shedding frequencies based on the current velocity can be calculated and compared with...
the response frequencies identified from the spectrum. In case of current-induced VIV, the response frequency is expected to be in agreement with the shedding frequencies calculated from current velocities. In this way we can identify the current-induced VIV from vessel motion-induced VIV. The logger S01 placed on the vessel measures the vessel acceleration. The frequency of the vessel motion can be found by a spectrum analysis at this logger.

The velocities are obtained by the integration of the accelerations. Further integration provides the displacements at various logger locations. Once the velocities along the riser are known, the equivalent current profile can be generated and this can be used for the VIVANA analysis. The empirical model is then applied to the case to predict the response frequency. It should be noted that the vessel motions in this case need not necessarily be limited to low KC numbers. Nevertheless, the empirical model is applied and validated based on the theory that the model holds true for higher KC numbers as well.

The accelerations are passed through a low pass filter to filter out frequencies less than 0.5 Hz, which are of our interest. This will eliminate the vibrations of high frequencies, especially that caused by the drill string. Typically to identify the VIV, it is sufficient to filter out only the frequencies in the VIV range. Since we are also interested in the vessel motion, which can occur at very low frequencies, we have to consider those as well.

A typical acceleration spectrum from one of the loggers located on the riser is presented in Figure 5.5. The spectrum gives a glimpse of the various frequency contributions to the riser response. The vessel motion occur 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 purely measures the vessel acceleration and hence vessel motion frequency can be singled out.
5.4 Methodology

The methodology followed for the numerical analysis is summarized as follows:

- Obtain the velocity time series at each logger location. Generate the equivalent current profile based on the Equation 3.3.
- Obtain the KC number distribution along the riser from the displacements derived at each logger location.
- Choose the appropriate value of N from Table 3.1 based on the KC distribution.
- Estimate $f_{resp}$ from the value of $f_{im}$ and N.
- Calculate initial $St^*$ and perform VIVANA analysis, iterate $St^*$ to obtain $f_{dom} = f_{resp}$
5.5 Results and Discussion

In this section four representative events are identified and analysed. All these four events belong to the operational case of drilling of well-1 and are presented in Table 5.2. The empirical model is validated against the measured responses of the riser. In the validation studies, emphasis is given to the prediction of response frequency. The eigen frequencies for the first 10 modes and the normalized mode shapes for the first 5 modes are presented in Figures 5.6 and 5.7 respectively.

![Eigen modes and eigen frequencies for the drilling riser](image)

**Figure 5.6** Eigen modes and eigen frequencies for the drilling riser

![Normalized mode shapes for the drilling riser](image)

**Figure 5.7** Normalized mode shapes for the drilling riser
Table 5.2 Events considered for analysis

<table>
<thead>
<tr>
<th>Event</th>
<th>Time stamp</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>58</td>
<td>17/04/2007 1800 hrs</td>
<td>Vessel motion-induced VIV dominant</td>
</tr>
<tr>
<td>612</td>
<td>02/06/2007 0200 hrs</td>
<td>Vessel motion-induced VIV dominant</td>
</tr>
<tr>
<td>413</td>
<td>17/05/2007 0800 hrs</td>
<td>Vessel motion-induced VIV dominant</td>
</tr>
<tr>
<td>434</td>
<td>19/05/2007 0200 hrs</td>
<td>Current-induced VIV dominant</td>
</tr>
</tbody>
</table>

5.5.1 Vessel motion-induced VIV dominant cases

5.5.1.1 Event 58

Event 58 corresponds to a very low current velocity case. In Figure 5.8, the ocean current is compared with the equivalent current profile generated based on the velocities derived from the accelerations. It can be seen that the ocean current velocities are very low compared with the velocities from vessel motion. The shedding frequency due to ocean current has a maximum value of 0.043 Hz.

![Graph showing ocean current and equivalent current profiles](Figure 5.8)

**Figure 5.8** Generated equivalent current profile and the ocean current profile (Event 58)

Figure 5.16 and Figure 5.17 represent the spectra of accelerations in X and Y directions respectively across all the 13 loggers. 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 (highlighted by the blue square). This is identified to be the response frequency of the VIV.
Figure 5.9 Spectra of acceleration in X direction across all loggers (Event 58)

Figure 5.10 Spectra of acceleration in Y direction across all loggers (Event 58)
In order to predict the VIV response due to vessel motions, it is necessary to identify the vessel motion frequency \((f_{im})\) and the KC number distribution along the riser. As per the proposed model, these parameters determine the response frequency \((f_{resp})\). Figure 5.11 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. From the figure \(f_{im}=0.0033\) Hz, which is reasonable for a MODU’s slow varying motion due to the second order differential frequency loads.

![Displacement spectrum of logger S01 (Event 58)](image)

Figure 5.11 Displacement spectrum of logger S01 (Event 58)

Figure 5.12 shows the KC number distribution along the riser. As expected, since the vessel drift is of a larger amplitude, we have very high KC numbers. In order to apply the model and to predict the response with reasonable accuracy, it is necessary to define the representative KC number from the given distribution. This will define the value of \(N\) and in turn the predicted value of \(f_{resp}\). As discussed in section 3.2.2, we take the midpoint of distribution as the representative KC. In this case we take it to be 203. Following the findings of Sumer and Fredsøe (2006), we get the value of \(N\) to be 26. Applying Equation 3.1, the value of \(f_{resp}\) is equal to 0.08668 Hz. This is the peak frequency that was found from the spectrum. Hence, it is possible to predict the response frequency of a full-scale riser using the empirical model.

Figure 5.13 shows the excitation frequencies from VIVANA compared with the peak frequency
Figure 5.12 KC number distribution along the riser (Event 58) from the displacement amplitude spectrum of logger S07. The frequencies are presented above 0.04 Hz in the spectrum as the peak at lower frequencies is very large because of the vessel displacement and here only the frequencies in VIV range are of interest. A very good agreement is achieved with the analysis and measurements. The dominant mode here is the 6th mode. A peak can be seen at 0.045 Hz. This falls in the wave-frequency range of 0.04-0.2 Hz and thus could be the response from wave induced motion.

Figure 5.13 Excitation frequencies along the riser compared with displacement spectrum at logger S07 (Event 58)

Figure 5.14 shows the RMS A/D of the riser due to VIV. On comparing the RMS A/D
from the measurements and the numerical analysis at the lower part where the loggers are concentrated and measurements are available for comparison, we can see that the mode shape from the predicted response agrees well with the mode shape from the measurements. It is to be noted that the amplitudes of vibration from the numerical analysis is reduced by 60% based on the findings in case of irregular waves (Sumer and Fredsøe, 2006, p. 441-442).

As mentioned before, the major goal of the validation was to prove that the empirical model could predict the response frequency and the associated mode with reasonable accuracy. In this case, it could predict the response frequency accurately. The mode shape also matches well with the mode shape from the measurements although we could not get a good agreement in terms of amplitudes.

### 5.5.1.2 Event 612

Event 612 is also a low current case like the previous one. Figure 5.15 shows the comparison of equivalent current profile generated from the acceleration measurements and the ocean current profile. The shedding frequency due to ocean current has a maximum of 0.1 Hz at the point of maximum current velocity, but otherwise ranges from 0.002-0.05 Hz.
Figure 5.15 Generated equivalent current profile and the ocean current profile (Event 612)

Figures 5.16 and 5.17 show the acceleration amplitude spectra in X and Y directions respectively. It can be seen that the dominant response occur at frequencies of 0.054 Hz, 0.063 Hz and 0.1122 Hz.

Figure 5.16 Spectra of acceleration in X direction across all loggers (Event 612)
Figure 5.17 Spectra of acceleration in Y direction across all loggers (Event 612)

Figure 5.11 shows the displacement amplitude spectrum of logger S01. From the plot, the frequency of vessel motion in this case is found to be 0.0022 Hz.

Figure 5.18 Displacement spectrum of logger S01 (Event 612)
The KC number distribution is shown in Figure 5.19. The representative KC in this case is also taken to be the midpoint of the distribution (refer section 3.2.2). Here, the KC number considered for the empirical model is 408, which means the value of N is 51. Hence, as per the model, the response frequency predicted is 0.1133 Hz. This frequency is close to one of the peaks of the spectrum. Thus it can be inferred that based on the KC distribution and empirical model, the dominant response is 0.1133 Hz.

![Figure 5.19 KC number distribution along the riser (Event 612)](image)

In Figure 5.20, the excitation frequencies from numerical analysis is compared with the displacement spectrum of logger S05. The dominant response frequency from analysis matches with the peak frequency from the measurements. The dominant mode here is the 7th mode. The empirical model was able to predict the response based on the KC number distribution and vessel motion frequency. It should be noted that there were three peaks in the spectrum and from the model it is identified that 0.1122 Hz is the one causing the vessel motion-induced VIV. This is proved from the mode shape obtained from the measurements (refer Figure 5.21), which corresponds to the above mentioned frequency. The other two peak frequencies fall in wave-frequency range and could be the response from wave induced motion.
Figure 5.20 Excitation frequencies along the riser compared with displacement spectrum at logger S05 (Event 612)

Figure 5.21 Comparison of RMS A/D along the riser (Event 612)

The comparison of RMS A/D from the analysis and measurements are presented in Figure 5.21. It can be seen, at the bottom part where measurements are available, that the mode
shape from the two is in good agreement. As in the previous case, the amplitudes from the analysis are reduced by 60% since this is caused by irregular motion. Although the amplitudes from the analysis and the measurements do not match, the main goal of predicting the correct mode has been achieved.

5.5.1.3 Event 413

Figure 5.22 shows the comparison of equivalent current from the vessel motion and the ocean current for Event 413.

![Generated equivalent current profile and the ocean current profile (Event 413)](image)

It can be seen that the maximum velocity of ocean current is almost similar in magnitude to the velocity of vessel motion. As such, this case cannot be adjudged as a case of pure vessel motion-induced VIV or of pure current-induced VIV. A look at Figure 5.23, which compares the vortex shedding frequencies, reveals that both the current profiles can excite similar frequencies of vibration.
Figures 5.24 and 5.25 present the spectra of accelerations in X and Y directions. Peaks could be identified at 0.0833 Hz, 0.068 Hz and at some frequencies in the lower range.
Figure 5.24 Spectra of acceleration in X direction across all loggers (Event 413)

Figure 5.25 Spectra of acceleration in Y direction across all loggers (Event 413)
The empirical model is applied to the event to predict the response and is compared with the response frequencies from the measurements. Figure 5.26 represents the displacement amplitude spectrum from the logger S01. Vessel motion is identified to be with a frequency of 0.00223 Hz.

![Figure 5.26 Displacement spectrum of logger S01 (Event 413)](image)

The KC number distribution is shown in Figure 5.27. We take the representative KC to be the midpoint value as discussed in section 3.2.2. The midpoint value here is 319 which leads to a value of 40 for the ratio N. Hence, the response frequency can be estimated to be 0.0889 Hz.

![Figure 5.27 KC number distribution along the riser (Event 413)](image)
The excitation frequencies are presented in Figure 5.28 and is compared with the displacement spectrum of logger S09. The response predicted using the model is in close agreement with the peak response from the accelerations. The dominant mode here is the 6th mode.

![Excitation frequencies along the riser compared with displacement spectrum at logger S09 (Event 413)](image)

**Figure 5.28** Excitation frequencies along the riser compared with displacement spectrum at logger S09 (Event 413)

The comparison of RMS A/D in Figure 5.29 shows that the mode shape from analysis agrees well with that obtained from the measurements.

![Comparison of RMS A/D along the riser (Event 413)](image)

**Figure 5.29** Comparison of RMS A/D along the riser (Event 413)
A good agreement is achieved with the response predicted by the numerical analysis and the one obtained from the measured data. Here both the ocean current and the vessel motion could induce VIV with a frequency close to the one obtained from data. The proposed empirical model was able to predict the frequency of vessel motion-induced VIV which is validated by the measured results. Though it is uncertain whether the current or the vessel motion causes VIV here, we were able to predict the response due to one of the contributing factor.

5.5.2 Ocean current-induced VIV dominant cases

5.5.2.1 Event 434

Event 434 is a high current case with a very low velocity of vessel motion. Figure 5.30 shows the comparison of current velocities for equivalent current and ocean current. Here, the equivalent current due to vessel motion is very less compared to the ocean current. Hence, in this case the VIV could be purely due to the current.

![Figure 5.30 Generated equivalent current profile and the ocean current profile (Event 434)]
Figures 5.31 and 5.32 show the acceleration spectrum across the loggers in X and Y direction respectively. The peak response can be found at a frequency of 0.084 Hz.

Since vessel motion is not the cause of VIV here, this can be analysed based on the ocean current velocity. The ocean current profile is used with an $St$ value of 0.2 to predict the VIV. Figure 5.33 shows the excitation frequencies along the length of the riser due to the current. The displacement spectrum of the logger S03 is also presented to compare the dominant frequencies. The current, albeit of high velocity, is heavily sheared and reduces to negligible velocity after a depth of 600 m. Thus the dominant frequency is present at the top part of the riser as the rest of the riser encounters a very low velocity and shedding frequency. The dominant response frequency from the analysis corresponds well with the response frequency found from the measurements.

![Figure 5.31 Spectra of acceleration in X direction across all loggers (Event 434)](image-url)
Figure 5.32 Spectra of acceleration in Y direction across all loggers (Event 434)

Figure 5.33 Excitation frequencies along the riser compared with displacement spectrum at logger S03 (Event 434)

Figure 5.34 presents the comparison of RMS A/D from the measurements and the analysis.
Though the amplitude is not equal, the mode shape from both cases is similar to each other which is evident when comparing the lower part of the riser.

![Figure 5.34 Comparison of RMS A/D along the riser (Event 434)](Image)

5.5.3 Discussion

Vessel motion-induced VIV during a full-scale drilling scenario is firstly identified. The validation of the proposed empirical model using the full-scale drilling riser measurements was performed and the results point out that the model can be extended to a long riser in its actual operational environment. Although the full-scale riser under study was subjected to flow of high KC numbers, the model was applied and validated as it is generic and applicable in all KC ranges. The vessel motion-induced VIV could be identified in the some cases and response frequencies were predicted using the model. In all cases, the response frequencies and the mode shape from the measurements were in good agreement with the ones predicted using the empirical model.

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. (2008) and Thethi et al. (2005) based on riser monitoring data were focussed only on finding the response in the VIV frequency range. Typically, the accelerometers are not accurate in low frequencies, but the vessel displacements obtained by integration is within the range of typical vessel drifts.
Chapter 6

Numerical VIV Prediction of Deep Sea Mining Riser

6.1 Introduction

In the previous chapters, the proposed empirical model was validated against small-scale model tests and full-scale riser measurements. The results obtained gives confidence to apply the procedure to predict the vessel motion-induced VIV of an ultra-long deep sea mining riser. As mentioned in Chapter 1, the VIV is a major concern for the free-hanging mining riser. With the mining industry targeting deeper waters in the world’s oceans, focus on improving the existing technology to prevent such concerns is vital. In this chapter, the empirical model is applied to a 5,000 m long deep sea mining riser. The configuration of the riser is adopted from the at-sea experiments conducted in the North Pacific Ocean in the 1970s (Chung, 2010). The focus is mainly on vessel motions in low KC number ranges where the empirical model holds high significance. The surge and sway motions of the support vessel depends largely on the type of sea-keeping used. For deep sea mining support vessels, dynamic positioning is more practical and hence low KC number scenarios are possible.
6.2 Riser Configuration

The riser is deployed from the moon pool of a production support vessel. The riser is pinned at the top with rotation around the longitudinal axis restricted. The bottom end is free and a buffer weight is placed at the bottom of the riser for stability. The buffer usually contains the pumping equipment and typical weight of the buffer is obtained from literature (Chung et al., 1994). The resistance offered by the flexible hoses connected to the SPTs is quite minimal and is neglected here. Figure 6.1 shows the configuration of the riser.

![Configuration of the riser](image)

**Figure 6.1** Configuration of the riser
The dimensions and properties of the riser are given in Table 6.1.

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>5000</td>
<td>m</td>
</tr>
<tr>
<td>Outer diameter</td>
<td>0.38</td>
<td>m</td>
</tr>
<tr>
<td>Inner diameter</td>
<td>0.19</td>
<td>m</td>
</tr>
<tr>
<td>Cross-sectional area, A</td>
<td>0.085</td>
<td>m²</td>
</tr>
<tr>
<td>Modulus of elasticity, E</td>
<td>$2.07 \times 10^{11}$</td>
<td>N/m²</td>
</tr>
<tr>
<td>Bending stiffness, EI</td>
<td>$1.98 \times 10^{8}$</td>
<td>Nm²</td>
</tr>
<tr>
<td>Tensioning stiffness, EA</td>
<td>$1.76 \times 10^{10}$</td>
<td>N</td>
</tr>
<tr>
<td>Mass/unit length in air</td>
<td>667.7</td>
<td>kg/m</td>
</tr>
<tr>
<td>Mass of buffer in air</td>
<td>203.2</td>
<td>tons</td>
</tr>
</tbody>
</table>

### 6.3 Simplifications and Assumptions

Following simplifications and assumptions are used in the analysis:

1. In real cases, the riser has an asymmetry because of cables running along its length and pumps installed off-center of the riser (Chung and Tsurusaki, 1994). In the analysis, the effect of asymmetry is not considered and riser is assumed to be symmetric along its axis.

2. The top end of the riser is assumed to be at the still water level and the whole length is submerged in water.

3. IL VIV is not considered in the analysis. IL responses, apart from being smaller in magnitude compared to CF VIV, are in the direction of the vessel motion. The frequency of vessel motion is dominant and thus IL frequency can be neglected. Hence, only CF VIV is of interest in the present analysis.
6.4 Case Studies

In the analysis, the riser is subjected to various imposed motions - both regular and irregular. Low KC number cases are being considered here and as such the vessel drift in all cases are quite small. Three cases of simple harmonic surge motion at different frequencies are studied along with a low frequency irregular motion case. Finally, the VIV due to pure current is investigated to compare the stresses and fatigue caused by vessel motion-induced VIV with that of current-induced VIV.

The methodology followed for the analysis is similar to the one followed in Chapter 4. The dynamic analysis of the modelled riser is conducted in RIFLEX to obtain the displacements at each node of the riser. The velocity time series are then derived at each node. Then, the equivalent current profile is generated based on Equation 3.3. Finally, the proposed empirical model is followed to predict the VIV response in VIVANA (refer Figure 3.6). The midpoint of the KC distribution is taken to be the representative KC range.

The eigen frequencies of the riser and the normalized mode shapes are presented in Figures 6.2 and 6.3 respectively.

![Figure 6.2 Eigenmodes and eigen frequencies for the deep sea mining riser](image)
6.4.1 Regular motion case with $A=1.5$ m

In this case study, we consider harmonic surge motion of the vessel with an amplitude of 1.5 m. The KC number at the top is thus found to be 24.8. Two periods of motion are studied in the case - with 6 s and with 12 s. The details of the vessel motion are presented in Table 6.2.

<table>
<thead>
<tr>
<th>Amp (m)</th>
<th>T (s)</th>
<th>$f$ (Hz)</th>
<th>$KC_{top}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>6</td>
<td>0.1667</td>
<td>24.8</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>0.0833</td>
<td></td>
</tr>
</tbody>
</table>

The generated equivalent current profiles for both the frequencies are shown in Figure 6.4. The motion with higher frequency has the higher velocities.
Figure 6.4 Equivalent current profile (regular motion case with $A=1.5\ m$)

Figure 6.5 KC number distribution (regular motion case with $A=1.5\ m$)

Figure 6.5 compares the KC number distribution along the riser due to both the frequencies. Although the top KC number is same, variation in KC is different for both the cases since
in the lower frequency case the riser is displaced more than the higher frequency case. The midpoint of both KC distribution fall in the range of 7-15 and hence, we select N=2 from Table 3.1.

Applying Equation 3.1, we get:
For $T=6$ s, $f_{resp} = 0.33$ Hz, and
For $T=12$ s, $f_{resp} = 0.17$ Hz

The value of $St^*$ calculated for the response is 0.12 in this case study.

Figure 6.6 presents the excitation frequencies along the riser obtained from the VIVANA analysis. The dominant response frequencies are the ones predicted using the model. Heavy shear in the current profile for the case with $T=6$ s resulted in the lower shedding frequencies at the lower part of the riser. As such the dominant response frequency is allocated a zone at the top part of the riser.

![Figure 6.6](image_url)

**Figure 6.6** Excitation frequencies (regular motion case with $A=1.5$ m)

The RMS A/D of the riser is shown in Figure 6.7. The higher frequency motion has a comparatively lower amplitude of vibration than the lower frequency motion. Large variations in amplitudes can be seen at the bottom of the riser, which is free to move.
The strain distribution along the length of the riser is presented in Figure 6.8. The value remains nearly a constant for almost the initial 3000 m of the riser, but experiences a sharp
increase at the bottom part. For both $T=6$ s and $T=12$ s, the highest value of strain is obtained at the bottom most part of the riser, which experiences a large variation in amplitude. This variation causes the curvature, which is the double differential of amplitude, to be high and results in high strains.

The fatigue analysis of the riser was conducted and the fatigue damage along the riser is shown in Figure 6.9. The fatigue is calculated using the DNV SN curve B1 (DNV RP C203, 2010) for structure in seawater with free corrosion. The values used in the SN curve are:

- Negative inverse slope of the SN curve, $m = 3.0$

- Intercept of log $N$ axis, $\log \bar{a} = 12.436$

The minimum fatigue life occurs at the bottom of the riser, which is subjected to the maximum strain. The minimum fatigue life at the bottom portion is 117.7 years for $T=6$ s and 1603.1 years for $T=12$ s.

![Fatigue Damage (1/years)](image)

**Figure 6.9** Fatigue damage along the riser (regular motion case with $A=1.5$ m)
6.4.2 Regular motion case with A=2.5 m

In this case study, we consider harmonic surge motion of the vessel with an amplitude of 2.5 m. This will result in a top KC number of 41.3. Similar to the previous case study, two periods of motion are studied - with 6 s and with 12 s. The details of the vessel motion are presented in Table 6.3.

Table 6.3 Vessel motions for regular motion case with A=2.5 m

<table>
<thead>
<tr>
<th>Amp (m)</th>
<th>T (s)</th>
<th>f (Hz)</th>
<th>$KC_{top}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>6</td>
<td>0.1667</td>
<td>41.3</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>0.0833</td>
<td></td>
</tr>
</tbody>
</table>

Figure 6.10 shows the comparison of equivalent current profiles from both frequencies.

![Equivalent current profile (regular motion case with A=2.5 m)](image)

Figure 6.10 Equivalent current profile (regular motion case with A=2.5 m)

The KC number distribution in presented in Figure 6.11. Even though the top KC is above 40, the midpoint of the distribution falls in the range of 15-24 and hence this case qualifies as a case of low KC number. We select N=3 from Table 3.1.
Applying Equation 3.1, we get:
For $T=6s$, $f_{resp} = 0.5 \text{ Hz}$, and 
For $T=12s$, $f_{resp} = 0.25 \text{ Hz}$

The value of $St^*$ calculated for the response is 0.108 in this case study.
The excitation frequencies along the riser are shown in Figure 6.12. The response frequencies predicted using the empirical model is achieved in the analysis.

**Figure 6.13** RMS A/D along the riser (regular motion case with A=2.5 m)

**Figure 6.14** Strain along the riser (regular motion case with A=2.5 m)
The RMS A/D and the strains along the riser are presented in Figures 6.13 and 6.14 respectively. As expected the strains are maximum at the bottom of the riser where the variation in amplitude is quite high.

The fatigue damage is presented in Figure 6.15. The maximum fatigue damage occurs at the bottom of the riser. The minimum fatigue life in case of T=6 s is 111.4 years and T=12 s is 324.9 years.

![Fatigue Damage](image)

**Figure 6.15** Fatigue damage along the riser (regular motion case with A=2.5 m)

### 6.4.3 Regular motion case with A=5 m

This case deals with harmonic motion with an amplitude of 5 m and periods of 10 s and 15 s. The top KC number in this case is 82.6. Table 6.4 summarizes the details of the vessel motion.

<table>
<thead>
<tr>
<th>Amp (m)</th>
<th>T (s)</th>
<th>f (Hz)</th>
<th>KC\textsubscript{top}</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>10</td>
<td>0.1</td>
<td>82.6</td>
</tr>
<tr>
<td>5</td>
<td>15</td>
<td>0.067</td>
<td></td>
</tr>
</tbody>
</table>
Figure 6.16 represents the equivalent current profiles for both the imposed motion frequencies. The KC number distribution is shown in Figure 6.17, in which it is clear that the representative KC number falls in the range of 32-40. Hence, we can select N=5 for this case from Table 3.1.

Figure 6.16 Equivalent current profile (regular motion case with A=5 m)

Figure 6.17 KC number distribution (regular motion case with A=5 m)
Applying Equation 3.1, we get:

For $T=10$ s, $f_{\text{resp}} = 0.5$ Hz, and

For $T=15$ s, $f_{\text{resp}} = 0.33$ Hz

The value of $St^*$ calculated for the response is 0.09 in this case study.

Figure 6.18 shows the excitation frequencies along the riser. Drastically reducing current profiles in this case results in the dominant frequency to be present only on the top portion of the riser.

![Figure 6.18 Excitation frequencies (regular motion case with $A=5$ m)](image)

The RMS A/D and the strains along the riser are shown in Figures 6.19 and 6.20 respectively. It can be seen that the maximum values of RMS A/D for both the motion frequencies have their maxima at the top part of the riser. The variation in vibration amplitude is quite large at the bottom which results in large stresses and thus large strains at the bottom.
Figure 6.19 RMS A/D along the riser (regular motion case with A=5 m)

Figure 6.20 Strain along the riser (regular motion case with A=5 m)
The fatigue damage is presented in Figure 6.21. The maximum damage occurs at the free bottom portion of the riser where the stresses are higher. The minimum fatigue life is 107.5 years for $T=10$ s and 215.93 years for $T=15$ s.

### 6.4.4 Irregular motion case

In this case study, an irregular vessel motion is considered. Typically, the vessel drifts are of low frequency irregular motions. Focus is given on low KC number case and hence we consider a motion with smaller amplitude. Figure 6.22 shows the displacement spectrum of the irregular motion. The peak frequency of the motion is 0.0105 Hz ($T=95$ s).
The equivalent current profile due to the motion is presented in Figure 6.23. As this is a low amplitude motion with a low frequency, the velocities are quite low as expected. The bottom part of the riser, which is free to move, have a velocity similar in magnitude to the top. This is also a consequence of the low amplitude low frequency motion.
The KC number distribution is shown in Figure 6.24. The representative KC can be taken as 24 which gives N=4. Hence, the $f_{\text{resp}}$ is estimated to be 0.0422 Hz.

Figure 6.24 The KC number distribution along the riser (irregular motion case)

Figure 6.25 shows the response frequency along the riser. It can be seen that there is only one frequency excited along the whole length of the riser. This frequency, 0.048 Hz, is similar to the estimated $f_{\text{resp}}$ and belongs to 5th mode of the riser. Since the velocity of equivalent current is quite low, the vortex shedding frequency is also low and resulted in the excitation of a lower mode.
The RMS A/D and the strains along the riser are presented in Figures 6.26 and 6.27. The strains are very low in this case due to the curvature being very small. Still the maximum strain occurs at the bottom part which is free to move.
Figure 6.27 Strain along the riser (irregular motion case)

Figure 6.28 shows the fatigue damage along the riser and it can be seen that the damage is very small. The fatigue life of the riser in this case is quite high owing to the smaller stresses in the riser. The minimum fatigue life in this case is $1.15 \times 10^7$. 

Figure 6.28 Fatigue damage along the riser (irregular motion case)
6.4.5 Current-induced VIV case

In current-induced VIV case, the VIV due to pure ocean current is investigated. The typical current data pertaining to the Pacific Ocean is obtained from the archives of National Oceanographic Data Center (NODC, 2016). The data contains current velocities measured by ship mounted ADCPs. From the data, the sample with maximum current velocities has been selected for the purpose of this analysis. Figure 6.29 shows the ocean current profile.

The VIV due to the current is analysed in VIVANA to obtain the response. Figure 6.30 shows the excitation frequencies along the riser because of the vortex shedding due to the current flow. The ocean current is heavily sheared and reduces to negligible velocity as we go deeper. Hence, the top part of the riser experience higher frequencies whereas the lower part is excited by very low frequencies.
The strain values are plotted in Figure 6.31. The strain on the riser are quite small owing to the vibration at very low modes in the current. Low strain results in a very high fatigue life for the riser. The minimum fatigue life for the riser is 89248 years. The fatigue damage is presented in Figure 6.32.
6.5 Discussion

In this chapter, various cases of low KC vessel motions were considered and the behaviour of the deep sea mining riser with regard to the VIV was investigated. The high frequency motions were found to excite very high modes of vibrations.

A comparison of the case studies are presented in Table 6.5.

Table 6.5 Comparison of case studies

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Type</th>
<th>Amp (m)</th>
<th>T (s)</th>
<th>f (Hz)</th>
<th>KC range</th>
<th>N</th>
<th>f_{resp}</th>
<th>Mode</th>
<th>Min. fatigue life (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Regular motion</td>
<td>1.5</td>
<td>6</td>
<td>0.166</td>
<td>7-15</td>
<td>2</td>
<td>0.33</td>
<td>29</td>
<td>117.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>12</td>
<td>0.0833</td>
<td></td>
<td></td>
<td>0.17</td>
<td>15</td>
<td>1603.1</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>2.5</td>
<td>6</td>
<td>0.166</td>
<td>15-24</td>
<td>3</td>
<td>0.5</td>
<td>42</td>
<td>111.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>12</td>
<td>0.0833</td>
<td></td>
<td></td>
<td>0.25</td>
<td>22</td>
<td>324.9</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>5</td>
<td>10</td>
<td>0.1</td>
<td>32-40</td>
<td>5</td>
<td>0.5</td>
<td>42</td>
<td>107.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>15</td>
<td>0.0667</td>
<td></td>
<td></td>
<td>0.33</td>
<td>29</td>
<td>215.93</td>
</tr>
<tr>
<td>4</td>
<td>Irregular motion</td>
<td>5 (max)</td>
<td>95</td>
<td>0.105</td>
<td>24</td>
<td>4</td>
<td>0.0422</td>
<td>5</td>
<td>1.15 \times 10^7</td>
</tr>
<tr>
<td>5</td>
<td>Current</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.375</td>
<td>32</td>
<td>89248</td>
</tr>
</tbody>
</table>
When comparing the fatigue life from various cases, it can be seen that the high frequency vessel motion-induced VIV can cause considerable fatigue damage to the riser. The minimum fatigue life in the first three case studies is very low when compared to the current-induced VIV. This implies that the possibility of such motions could cause considerable damage to the riser and hence should be taken into consideration during design and operation. It can also be seen that the low frequency motion at low KC numbers causes quite minimal damage to the riser. The capability of the mooring system/dynamic positioning system decides to an extent the motion of the vessel. Hence, from an operational point of view it is important to limit the amplitude and the frequency of vessel drift in order to reduce the effects of VIV on the riser.
Chapter 7

Conclusions

Vortex Induced Vibration is a major concern for a riser exposed to a current flow. It can cause fatigue in the riser and lead to its failure. Studies have pointed out that the vessel motion can also induce VIV which can be of the same magnitude as that caused by the current flow. Hence, it is important that the VIV is identified for the riser and mitigation measures taken to suppress VIV.

An empirical model was proposed to predict the VIV of a riser due to vessel motions and was validated. From the experimental results from the small-scale riser model tests, it was possible to validate the numerical model. Of special interest were the cases with low KC numbers, where the frequency of response depends on the frequency of imposed motion. The validation provided good results with the model being able to predict the response frequencies accurately. The strain values were difficult to match as those were influenced by the actual structural damping and measurement errors. Despite of this, good comparisons were obtained for several of the cases.

The data obtained from the measurements of an actual full-scale drilling riser was analysed and in some cases vessel motion-induced VIV was identified. The proposed model was validated against these results and provided useful insights into the VIV behaviour of a full-scale riser under vessel motion. The results of the validation studies provided confidence in extending the numerical model to analyse the 5,000 m deep sea mining riser.
The analysis of the riser provided good insights into the behavior of such a long riser under pure vessel motions of low KC numbers. A long riser with many natural frequencies can lock-on to shedding frequencies due to a wide range of current velocities. The stresses and strains at the bottom are high which results in large fatigue damage and hence measures to suppress VIV are required. VIV suppression devices like helical strakes, fairings or perforated shrouds should be installed to avoid vortex shedding behind the riser. The VIV due to ocean current was also investigated and compared with the vessel motion-induced VIV. It should be noted that the configuration of the present investigated riser is similar to a disconnected drilling riser or a free-hanging water intake riser. Hence, the present study can be extended to other application areas as well.

A further study should address the coupled analysis of the support vessel - vertical riser system inorder to predict the global motions of the riser accurately. This will be an area of interest for future work. Furthermore, axial resonance, which is expected for the riser at the wave frequency range, can be investigated.


Appendix A

Small-scale Riser Model Tests:
Comparison of Eigen Frequencies

Table A.1 shows the comparison of eigen frequencies calculated from VIVANA and the ones obtained from the experimental analysis of Wang et al. (2016c) for the first 6 eigen modes for the Water Intake Riser.

<table>
<thead>
<tr>
<th>Eigen mode</th>
<th>From VIVANA</th>
<th>From the literature (Wang et al., 2016c)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time period (s)</td>
<td>Frequency (Hz)</td>
</tr>
<tr>
<td>1</td>
<td>75.18</td>
<td>0.0133</td>
</tr>
<tr>
<td>2</td>
<td>20.74</td>
<td>0.048</td>
</tr>
<tr>
<td>3</td>
<td>8.4</td>
<td>0.119</td>
</tr>
<tr>
<td>4</td>
<td>4.33</td>
<td>0.23</td>
</tr>
<tr>
<td>5</td>
<td>2.61</td>
<td>0.383</td>
</tr>
<tr>
<td>6</td>
<td>1.73</td>
<td>0.577</td>
</tr>
</tbody>
</table>

Table A.2 shows the comparison of eigen frequencies calculated from VIVANA and the ones obtained from the experimental analysis of Wang et al. (2016a) for the first 7 eigen modes for the Free-hanging riser.
Table A.2 Comparison of Eigen frequencies

<table>
<thead>
<tr>
<th>Eigen mode</th>
<th>From VIVANA</th>
<th>From the literature (Wang et al., 2016a)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time period (s)</td>
<td>Frequency (Hz)</td>
</tr>
<tr>
<td>1</td>
<td>6.04</td>
<td>0.1656</td>
</tr>
<tr>
<td>2</td>
<td>1.83</td>
<td>0.5464</td>
</tr>
<tr>
<td>3</td>
<td>0.90</td>
<td>1.1094</td>
</tr>
<tr>
<td>4</td>
<td>0.55</td>
<td>1.817</td>
</tr>
<tr>
<td>5</td>
<td>0.37</td>
<td>2.7382</td>
</tr>
<tr>
<td>6</td>
<td>0.26</td>
<td>3.8684</td>
</tr>
<tr>
<td>7</td>
<td>0.19</td>
<td>5.2036</td>
</tr>
</tbody>
</table>
Appendix B

Modelling of Drilling Riser

The dimensions and weights of the drilling riser stack-up are given in Table B.1. The dry weight and submerged weight of the riser provided along with the dataset (BP and 2H Offshore, 2008) are important parameters to be taken into account during the modelling of the riser in RIFLEX. The submerged weight and buoyancy determines the tension along the riser and the dry weight distribution determines the vibration response.

The riser was modelled in RIFLEX taking into account both the dry weight and submerged weight. The weight parameter input given in RIFLEX is the unit dry weight of the riser. The external area input of the cross-section was determined such that the resulting buoyancy is in accordance with the submerged weight provided in the dataset.

The properties of the riser flex joints are given in Table B.2.
### Table B.1 Riser dimensions and weights

<table>
<thead>
<tr>
<th>Item</th>
<th>L (m)</th>
<th>Stress diameter (m)</th>
<th>Thickness (m)</th>
<th>Hydrodynamic diameter (m)</th>
<th>Unit dry wt. (kg/m)</th>
<th>Unit submerged wt. (kg/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diverter</td>
<td>4.1</td>
<td>0.5334</td>
<td>0.02</td>
<td>0.5334</td>
<td>3114.72</td>
<td>0.00</td>
</tr>
<tr>
<td>16.7 ft Pup</td>
<td>5.1</td>
<td>0.5334</td>
<td>0.02</td>
<td>0.5334</td>
<td>706.76</td>
<td>614.88</td>
</tr>
<tr>
<td>Inner barrel</td>
<td>9.2</td>
<td>0.5334</td>
<td>0.02</td>
<td>0.5334</td>
<td>787.95</td>
<td>0.00</td>
</tr>
<tr>
<td>Outer barrel</td>
<td>30.4</td>
<td>0.6604</td>
<td>0.04</td>
<td>0.6604</td>
<td>863.10</td>
<td>750.89</td>
</tr>
<tr>
<td>Intermediate FJ</td>
<td>2.8</td>
<td>1.1938</td>
<td>0.35</td>
<td>1.1938</td>
<td>1904.01</td>
<td>1656.52</td>
</tr>
<tr>
<td>Termination joint</td>
<td>17.3</td>
<td>0.5334</td>
<td>0.02</td>
<td>0.5334</td>
<td>735.95</td>
<td>640.28</td>
</tr>
<tr>
<td>5 ft pup</td>
<td>1.5</td>
<td>0.5334</td>
<td>0.02</td>
<td>0.5334</td>
<td>1391.46</td>
<td>1210.49</td>
</tr>
<tr>
<td>20 ft pup</td>
<td>6.1</td>
<td>0.5334</td>
<td>0.02</td>
<td>0.5334</td>
<td>740.75</td>
<td>644.46</td>
</tr>
<tr>
<td>40 ft pup</td>
<td>12.2</td>
<td>0.5334</td>
<td>0.02</td>
<td>0.8636</td>
<td>614.44</td>
<td>534.56</td>
</tr>
<tr>
<td>BUOY3000</td>
<td>548.6</td>
<td>0.5334</td>
<td>0.02</td>
<td>1.2827</td>
<td>861.72</td>
<td>17.62</td>
</tr>
<tr>
<td>BUOY4000</td>
<td>228.6</td>
<td>0.5334</td>
<td>0.02</td>
<td>1.3081</td>
<td>904.98</td>
<td>27.54</td>
</tr>
<tr>
<td>BUOY5000</td>
<td>274.3</td>
<td>0.5334</td>
<td>0.02</td>
<td>1.3335</td>
<td>957.82</td>
<td>15.04</td>
</tr>
<tr>
<td>Slick</td>
<td>594.5</td>
<td>0.5334</td>
<td>0.02</td>
<td>0.8636</td>
<td>586.74</td>
<td>510.47</td>
</tr>
<tr>
<td>Lower FJ</td>
<td>2.7</td>
<td>1.4732</td>
<td>0.49</td>
<td>1.4732</td>
<td>2485.25</td>
<td>933.04</td>
</tr>
<tr>
<td>LMRP</td>
<td>3.4</td>
<td>5.6515</td>
<td>2.58</td>
<td>5.6515</td>
<td>29495.64</td>
<td>25661.20</td>
</tr>
<tr>
<td>BOP</td>
<td>7.2</td>
<td>5.6515</td>
<td>0.02</td>
<td>5.6515</td>
<td>26597.42</td>
<td>23139.76</td>
</tr>
<tr>
<td>Wellhead</td>
<td>4.4</td>
<td>0.9652</td>
<td>0.06</td>
<td>0.9652</td>
<td>1854.08</td>
<td>1613.09</td>
</tr>
</tbody>
</table>

### Table B.2 Properties of riser Flex Joints (BP and 2H Offshore, 2008)

<table>
<thead>
<tr>
<th>Item</th>
<th>Dry weight (kg)</th>
<th>Rotation stiffness (Nm/deg)</th>
<th>Submerged weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower FJ</td>
<td>-</td>
<td>105690</td>
<td>2531.09</td>
</tr>
<tr>
<td>Intermediate FJ</td>
<td>5356.56</td>
<td>18970</td>
<td>4660.29</td>
</tr>
<tr>
<td>Upper FJ</td>
<td>8762.64</td>
<td>21680</td>
<td>-</td>
</tr>
</tbody>
</table>
Appendix C

Hydrodynamic Coefficients used for Deep Sea Mining Riser

The drag coefficient $C_D$ and added mass coefficient $C_a$ used for the model are as follows

![Hydrodynamic force coefficients](image_url)

- Quadratic drag coefficients:
  - $CQ_x = 0.0$
  - $CQ_y = 1.2$
- Linear drag coefficients:
  - $CL_x = 0.0$
  - $CL_y = 0.0$
- Added mass coefficients:
  - $CA_x = 0.0$
  - $CA_y = 1.0$
Appendix D

MATLAB Codes for Acceleration Data Analysis

D.1 Low pass filter

```matlab
function [yfilt,filtb,filta] = filter1(filtertype,y,varargin)

% filter1 performs frequency or wavelength filtering on a 1D array using zero-phase Butterworth filtering.

% Syntax

% yfilt = filter1(filtertype,y,'fc',Fc)
% yfilt = filter1(filtertype,y,'lambdac',lambdac)
% yfilt = filter1(...,'fs',Fs)
% yfilt = filter1(...,'x',x)
% yfilt = filter1(...,'Ts',Ts)
% yfilt = filter1(...,'order',FilterOrder)
% [yfilt,filtb,filta] = filter1(...)

% Description

% yfilt = filter1(filtertype,y,'fc',Fc) filters 1D signal y using a specified filtertype and cutoff frequency Fc. For
% high-pass or low-pass filters Fc must be a scalar. For band-
% pass and band-stop filters Fc must be a two-element array. The
% filtertype can be
```

115
% 'hp' high-pass with scalar cutoff frequency Fc
% 'lp' low-pass with scalar cutoff frequency Fc
% 'bp' band-pass with two-element cutoff frequencies Fc
% 'bs' band-stop with two-element cutoff frequencies Fc

% yfilt = filter1(filtertype,y,'lambdac',lambdac) specifies cutoff
% wavelength(s) rather than cutoff frequencies. This syntax assumes
% lambda = 1/f.
% yfilt = filter1(...,'fs',Fs) specifies a sampling frequency Fs.
% If neither 'fs', 'x', nor 'Ts' are specified, Fs = 1 is assumed.
% yfilt = filter1(...,'x',x) specifies a vector of monotonically-
% increasing, equally-spaced sampling times or x locations corresponding
% to y, which is used to determine sampling frequency. If neither 'fs',
% 'x', nor 'Ts' are specified, Fs = 1 is assumed.
% yfilt = filter1(...,'Ts',Ts) specifies a sampling period or sampling distance
% such that Fs = 1/Ts. If neither 'fs', 'x', nor 'Ts' are specified,
% Fs = 1 is assumed.
% yfilt = filter1(...,'order',FilterOrder) specifies the order (sometimes
% called rolloff) of the Butterworth filter. If unspecified, FilterOrder = 1 is assumed.
% [yfilt,filtb,filtb] = filter1(...) also returns the filter numerator
% filt and denominator filt b.

% Author Info
% The filter1 function was written by Chad A. Greene of the University of
% Texas at Austin's Institute for Geophysics (UTIG), October 2015.
% http://www.chadagreene.com
%
% See also butter and filtfilt.

%% Initial error checks:
assert(license('test','signal_toolbox')==1,'The filter1 function requires Matlab''s Signal
Processing Toolbox. ')
assert(nargin>3,'Not enough input arguments. ')
assert(sum(strncmpi({'hp';'lp';'bp';'bs';'high';'low';'bandpass';'stop'},filtertype))==1,'Filter type must be ''hp'', ''lp'', or ''bp''. ')
assert(sum(strcmpi(varargin,'fc')) strcmpi(varargin,'lambdac'))==1,'Must declare a cutoff
frequency (or frequencies) ''fc'', or cutoff wavelength(s) ''lambdac''. ')
assert(isvector(y)==1,'Input y must be a vector. ')
%%% Define defaults:

order = 1;
Fs = 1;

%%% Parse Inputs:

%%% Replace filter type string if necessary:
filtertype = strrep(filtertype,'hp','high');
filtertype = strrep(filtertype,'lp','low');
filtertype = strrep(filtertype,'bp','bandpass');
filtertype = strrep(filtertype,'bs','stop');

%%% Is a sampling frequency defined?
tmp = strcmpi(varargin,'fs');
if any(tmp)
    Fs = varargin{find(tmp)+1};
end

%%% Define sampling period:
tmp2 = strcmp(varargin,'Ts');
if any(tmp2)
    Fs = 1/varargin{find(tmp2)+1};
end

%%% Define sampling vector:
tmp3 = strcmp(varargin,'x');
if any(tmp3)
    x = varargin{find(tmp3)+1};
    assert(isvector(x)==1,'Input x must be a vector.')
    assert(length(x)==length(y),'Dimensions of input vector x must match dimensions of input signal vector y.')
    Ts = unique(diff(x));
    assert(all([isscalar(Ts) isnfinite(Ts)])==1,'Input vector x must be equally spaced.')
    Fs = 1/Ts;
end

%%% Make sure user didn’t try to define a sampling frequency AND a sampling period:
assert(any(tmp)+any(tmp2)+any(tmp3)<2,'I am confused. It looks like you have attempted to define a sampling frequency and a sampling period. Check inputs of filter1.')

%%% Cutoff Frequency:
tmp = strcmpi(varargin,'fc');
if any(tmp)
    cutoff_freqs = varargin{find(tmp)+1};
end

tmp2 = strnmpi(varargin,'lambdac',4);
if any(tmp2)
    cutoff_freqs = 1./varargin{find(tmp2)+1};
end
assert((any(tmp)+any(tmp2)<2,'I am confused. It looks like you have attempted to define a
cutoff frequency and a cutoff period. Check inputs of filter1.'))

% Filter order:
tmp = strnmpi(varargin,'order',3);
if any(tmp)
    order = varargin{find(tmp)+1};
end

% Error checks on inputs:
assert(isscalar(Fs)==1,'Input error: Undefined sampling frequency or period.'))

switch filtertype
    case {'low','high'}
        assert(isscalar(cutoff_freqs)==1,'Low-pass and High-pass filters require a scalar
cutoff frequency.'))
    case {'stop','bandpass'}
        assert(numel(cutoff_freqs)==2,'Bandpass and bandstop filters require a low and high
frequency.'))
        cutoff_freqs = sort(cutoff_freqs);
    otherwise
        error('Unrecognized filter type.')</n
end

% Construct filter:

nyquist_freq = Fs/2;       % Nyquist frequency
Wn=cutoff_freqs/nyquist_freq; % non-dimensional frequency
[bfilt,filta]=butter(order,Wn,filtertype); % construct the filter
yfilt=filtfilt(bfilt,filta,y); % filter the data with zero phase

end
D.2 Fast Fourier Transform

```matlab
function [fre_plot, amp_plot] = fft_total(input, fs)

[m, n] = size(input);
N = n;
m = round(m/2)*2;

for i = 1:m
    fre(i) = i*fs/m;
end

fre1 = fre(1:m/2+1);
CF = zeros(m/2+1, N);
for i = 1:N
    CF1 = fft(input(:, i), m);
    CF(:, i) = abs(CF1(1:m/2+1)/(m/2+1));
    magCF(:, i) = angle(CF(:, i))/pi*180;
end

if N == 1
    mag_total = magCF;
else
    mag_total = sum(magCF');
end

fre_plot = fre1(1:round(m/2));
amp_plot = mag_total(1:round(m/2));
```
Appendix E

Full-scale Measurement Data Logger Specifications

The specifications of the data logger used for the full-scale measurements (BP and 2H Offshore, 2008) are provided in the following pages.
Overview

The 2H INTEGRI pod™-M is a standalone motion monitoring system. It allows movement of a structure to be recorded in its on-board memory over a long period of time (see examples). Data is downloaded into a computer for subsequent post data processing. The basic measurement includes:

- Tri axial acceleration (basic model)
- Tri plane angular rate (optional model)

From the measurements, various other parameters can be derived:

- Linear displacement
- Acceleration due to motion
- Average Inclination
- Harmonics

Deployment of loggers

The data logger contains all electronics, batteries and sensors enclosed in a cylindrical casing. After initialization using a computer, loggers can be deployed to the designated locations. This may simply involve strapping directly to the structure using bands or design of tailor-made interfaces to suit (available for diver or ROV operation for subsea use).

Mounting method

Strapped using suitable bands
Retrofit ROV friendly cradles

Cradle options

Strapped, bolted, magnetic holder

Analogue signal inputs

<table>
<thead>
<tr>
<th>Number of inputs</th>
<th>8 Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input range</td>
<td>0 – 2.5V</td>
</tr>
<tr>
<td>Accuracy / resolution</td>
<td>0.0012v/0.0006V</td>
</tr>
</tbody>
</table>

Memory disk reader

<table>
<thead>
<tr>
<th>Communication</th>
<th>Centronic (parallel) port</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case size</td>
<td>80mm x 140mm x 40mm</td>
</tr>
<tr>
<td>Case material</td>
<td>ABS</td>
</tr>
<tr>
<td>Power</td>
<td>PP3 9V batteries</td>
</tr>
<tr>
<td>Supply Current</td>
<td>7mA maximum</td>
</tr>
</tbody>
</table>

Format of downloaded data files

<table>
<thead>
<tr>
<th>Downloaded files</th>
<th>Time stamp files</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Data records for each session</td>
</tr>
<tr>
<td></td>
<td>Compatible with Excel</td>
</tr>
<tr>
<td></td>
<td>ASCII format</td>
</tr>
</tbody>
</table>

Format of data record files

| Data record file     | ASCII format, Raw voltages for all sensors inputs |

Maximum logging periods (examples)

| Continuous logging @ 50Hz | 50 days |
| Continuous logging @ 10Hz | 25 days |
| 10 minute logging every 0.5 hours @10Hz | 75 days |
### Specification

#### G Sensors
- **Sensor direction**: X, Y and Z
- **Range (g)**: ±1.2 and ±2
- **Cut-off response**: 4.5 Hz or configurable
- **Accuracy**: ±0.002 rms with ±2g range
- **AC temp effect**: No measurable effect
- **DC temp drift**: Calibration can be provided
- **Alignment error**: 0.3 deg between axis
- **Sensor-X direction**: Indicated on the logger body
- **Sensor calibration**: Use gravity (1g and -1g)

#### Angular rate sensors
- **Sensing direction**: X-Z, Y-Z and X-Y
- **Range**: +/- 10 deg/s (nominal)
- **Cut-off response**: 10Hz
- **Accuracy**: +/- 0.05 deg/s rms
- **Alignment error**: 0.3 deg

#### Data recording frequency
- **Record frequency [Hz]**: 30, 20, 15, 10, 5, 2
- **150 Hz on special request**
- **<± 0.5% of the frequency error**

#### Logging programme
- **Logging mode**: Continuous and intermittent
- **Log on period (min)**: 1, 10, 15, 20, 30
- **Cycle period (hour)**: 0.5, 1, 1.5, 2, 2.5, 3, 4, 5, 6

#### Communication ports
- **Port**: RS232 port
- **Connection method**: Standard RS232 cable

#### On-board memory
- **Memory media**: 128 Mb memory (standard)
- **-needs formatting by reader**

#### Software
- **Operating system**: Win95, 98, 2000, NT, XP
- **Functions**: -Diagnostic check of loggers
  - Initialise loggers
  - Download data from loggers
  - On-line logging
  - Battery/memory life calculation

#### Power supply
- **Batteries**: 2 D-size 3.6V lithium
- **Battery capacity**: 13.500mAh-hour nominal
- **Current (logging)**: 11-42mA (different sensors)
- **Standby**: 3mA maximum

#### Casing
- **Material**: Superduplex stainless steel
- **Size [mm]**: 60 diameter x 310 length
- **Weight in air**: 3.5kg (with batteries)
- **Weight in water**: 2.0kg (with batteries)
- **Direction of sensor-X**: Polarisation slot on base

#### Environmental
- **Operating**: 2º C to 30º C
- **Storage**: -5º C to 50º C
- **Pressure rating**: 3000 m water depth
- **Seals**: 3 ‘O-rings’ on cap