VORTEX-INDUCED VIBRATION CHARACTERISTICS OF TWO TANDEM SPRING SUPPORTED CYLINDERS WITH HELICAL STRAKES

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DEDICATION

This thesis is dedicated to my amazing husband, Muhammad Aizat Bin Mohd Khalid who shows me every day that dreams can come true, who continually provide his moral, spiritual, strength and financial support. This dedication is also shared with my wonderful, cheerful, talkative, and brilliant son, Muhammad Naufal Iman who inspires me every day.

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ABSTRACT

Vortex-induced vibration (VIV) response can occur when a structure interacts with a fluid flow, resulting in fatigue damage. The use of multiple cylinders during drilling operations worsens the situation due to the flow interference between the cylinders, and the response may become more complex than with a single-cylinder. The industry has been challenged to minimise the effect of flow interference on the structure, which is highly dependent on the separation distance between the cylinders. The purpose of this study is to investigate the VIV on two spring supported cylinders in the tandem configuration besides examining the performance of helical strakes in reducing the cylinders' vibration. A series of experiments were conducted in the water flume using circular cylinders, where both cylinders were free to oscillate in the cross-flow direction only under subcritical Reynolds number. The flow interference test was performed with separation distances of 3.5, 4.0, and 4.5*D*, where *D* is the cylinder's diameter, and the critical separation distance was identified. The experimental results including the displacement response, frequency response, and power spectral density, were compared to those of the cases involved with the single-cylinder. The influence of different helical strakes' arrangements was examined using the same method as in bare cylinders. The experimental results showed that the amplitude response of cylinders in tandem grew continuously as the reduced velocity increased for all separation distances, indicating the presence of wake-induced vibration (WIV). The lower branch of amplitude response, which was usually present in a single-cylinder, was discovered to be absent. The results also proved that when multiple cylinders were used, the cylinders would vibrate stronger than when the single-cylinder was used. The trailing cylinder vibrated slower than the leading cylinder for all separation distances due to the shielding effect of the leading cylinder. Additionally, the critical separation distance was determined at 3.5*D*, where the bistable regime existed. During this regime, two flow patterns appeared intermittently, with a flow transition between vortex formation from the leading cylinder and reattachment of boundary layer, leading to a considerable oscillation amplitude. Meanwhile, the helical strakes successfully reduced the oscillation amplitude for both cylinders at the critical separation distance. However, the effectiveness of the helical strakes was highly dependent on the strakes' arrangements. The present study found that the strakes had a significant suppressive effect when installed at the leading cylinder (arrangement of leading straked and trailing bare cylinders (LS+T)) or both cylinders (arrangement of two tandem straked cylinders (LS+TS)). The novelties of the study are: (1) the investigation of two cylinders' responses that both can move in the CF direction, which is new in the literature and (2) the evaluation of the suppression performance of helical strakes in critical separation distances for tandem rigid cylinders at different arrangement of strakes. Since most of the risers in offshore industries are not in a fixed condition, investigating the VIV of the oscillating cylinders is feasible. The findings are valuable to offshore engineers to forecast the VIV phenomenon of the oscillating cylinders, especially in a critical condition.

ABSTRAK

Tindak balas getaran vorteks induksi (VIV) akan berlaku apabila struktur berinteraksi dengan aliran bendalir, mengakibatkan kerekahan. Penggunaan beberapa silinder semasa operasi penggerudian memburukkan keadaan kerana kewujudan gangguan aliran di antara silinder, dan tindak balas menjadi lebih kompleks berbanding dengan silinder tunggal. Industri mengalami kesukaran untuk meminimumkan kesan gangguan aliran ini ke atas struktur, yang mana berkait rapat dengan jarak pemisahan di antara silinder. Tujuan kajian ini adalah untuk mengkaji getaran vorteks induksi pada dua silinder yang disokong menggunakan spring dalam kedudukan selari selain menguji prestasi jaluran heliks dalam mengurangkan getaran silinder. Ekperimen ini dijalankan dalam saluran air menggunakan silinder bulat, di mana kedua-dua silinder bebas bergetar dalam arah aliran silang sahaja dalam nombor Reynolds subkritikal. Ujian gangguan aliran dilakukan pada jarak pemisahan 3.5, 4.0 dan 4.5*D*, di mana *D* ialah diameter silinder, dan jarak pemisahan kritikal telah dikenal pasti. Keputusan ekperimen, termasuk tindak balas amplitud, tindak balas frekuensi, dan ketumpatan kuasa spektrum, dibandingkan dengan silinder tunggal. Pengaruh susunan jaluran heliks yang berbeza telah diuji menggunakan kaedah yang sama seperti silinder kosong. Penyelidikan ini mendapati bahawa tindak balas amplitud silinder dalam kedudukan selari terus meningkat apabila halaju meningkat untuk semua jarak pemisahan, menunjukkan kehadiran getaran gelombang induksi (WIV). Tindak balas amplitud cabang bawah, yang biasanya terdapat dalam silinder tunggal, didapati tidak muncul. Keputusan juga membuktikan bahawa penggunaan lebih dari satu silinder, silinder akan bergetar dengan lebih kuat. Silinder belakang bergetar lebih perlahan daripada silinder hadapan pada semua jarak pemisahan yang disebabkan oleh kesan perlindungan daripada silinder hadapan. Selain itu, jarak pemisahan kritikal adalah 3.5*D*, di mana bistabil telah wujud. Dalam keadaan ini, dua corak aliran muncul secara berselang-seli, iaitu peralihan aliran antara pembentukan vorteks dari silinder hadapan dan pelekatan semula lapisan bendalir, yang membawa kepada amplitud getaran yang besar. Sementara itu, jaluran heliks berjaya mengurangkan amplitud getaran untuk kedua-dua silinder pada jarak pemisahan kritikal. Walau bagaimanapun, keberkesanan jaluran heliks ini sangat bergantung pada susunan jaluran heliks. Kajian ini mendapati bahawa jaluran heliks mempunyai kesan pengurangan getaran yang ketara apabila dipasang pada silinder hadapan (susunan silinder hadapan berjalur heliks dan silinder belakang yang kosong (LS+T)) atau kedua-dua silinder (susunan dua silinder berjalur heliks (LS+TS)). Novelti kajian ini adalah: (1) kajian tentang tindak balas dua silinder yang bebas bergetar dalam arah aliran silang, adalah baru di dalam literatur dan (2) penilaian prestasi pengurangan getaran dengan menggunakan jaluran heliks pada jarak pemisahan kritikal untuk silinder tegar dalam kedudukan selari pada susunan jaluran heliks yang berbeza. Memandangkan paip gerudi dalam industri luar pesisir tidak berada dalam keadaan tetap, kajian VIV terhadap silinder bergetar perlu dilaksanakan. Penemuan kajian ini bermanfaat kepada jurutera luar pesisir untuk meramalkan fenomena VIV bagi silinder bergetar, terutamanya dalam keadaan kritikal.

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LIST OF ABBREVIATIONS

1DOF	-	one-degree of freedom
2S	-	two single vortices
2P	-	two pairs of vortices
CF	-	cross-Flow
DFT	-	Discrete Fourier Transform
FFT	-	Fast Fourier Transform
FIV	-	Flow-induced vibration
IL	-	in-line
PSD	-	power spectral density
USB	-	Universal Serial Bus
P + S	-	one pair and a single vortex
PVC	-	Poly Vinyl Chloride
SSHR	-	Self-Standing Hybrid Riser
TLP	-	Top Leg Platform
TTR	-	Top Tensioned Riser
VIV	-	Vortex-induced vibration
WIV	-	Wake-induced vibration

LIST OF SYMBOLS

A^*	-	amplitude ratio
A_y	-	amplitude of the cylinder at cross-flow direction
a	-	acceleration
c	-	structural damping coefficient
C_d	-	drag coefficient
$C_{d\ mean}$	-	mean drag coefficient
C_l	-	lift coefficient
$C_{l\ fluct}$	-	fluctuating lift coefficient
D	-	outer diameter
d	-	inner diameter
F_d	-	drag force
F_l	-	lift force
f	-	frequency
f_n	-	natural frequency
f_s	-	vortex shedding frequency
f^*	-	frequency ratio
h	-	strakes height
k	-	spring stiffness
k_{Total}	-	total spring stiffness of the system
L	-	submerged length
L/D	-	aspect ratio
l	-	total length
m	-	total cylinder weight including a ball bearing block and a shaft
m_{Total}	-	total mass of the structure
m^*	-	mass ratio of cylinder
P	-	pressure
p	-	strakes pitch
Re	-	Reynolds number
S/D	-	separation distance between the cylinders
St	-	Strouhal number

Ti	-	turbulence intensity
U	-	flow velocity
U_r	-	reduced velocity
μ	-	dynamic viscosity of the fluid
ϕ	-	phase difference
ρ	-	fluid density
ζ	-	damping factor

CHAPTER 1

INTRODUCTION

1.1 Research background

Oceans are teeming with enormous oil and gas resources, necessitating an annual increase in industrial oil extraction. The extraction of oil and gas from the remains of marine algae and land plants began in the mid-19th century, with 147 billion tonnes of oil have been pumped from reserves around the world. The growth of oil and gas demand has increased prices due to the complex extraction process and expensive method used, especially as drilling oil and gas operations have moved to deeper water depths. For instance, the Cheyenne gas field in the Gulf of Mexico remarks the deepest drilling operation of 2740 metres. The design and technology of offshore drilling have evolved to develop oil and gas reserves through thousands of metres of thick rock layers.

A marine riser is critical in the offshore industry because it transports crude oil and natural gas produced by subsea oil wells to the surface processing facilities. There are two types of risers which are rigid and flexible. Additionally, the riser can be categorised into different configurations based on its application in the ocean, as shown in Figure 1.1. It can be a free-standing riser, top tensioned risers (TTRs), catenary risers, and hybrid riser towers (Miller, 2017). Some configurations allow installation with one or more risers, either rigid or flexible riser, or a combination of rigid and flexible risers. In these riser systems, all types of risers submerged in water can experience pressure differences on the pipe’s external surface due to current, resulting in hydrodynamic loads. Furthermore, the riser must withstand expansion and fatigue damage caused by unexpected sea movements, which can lead to fracture failure due to the vortex-induced vibration (VIV).

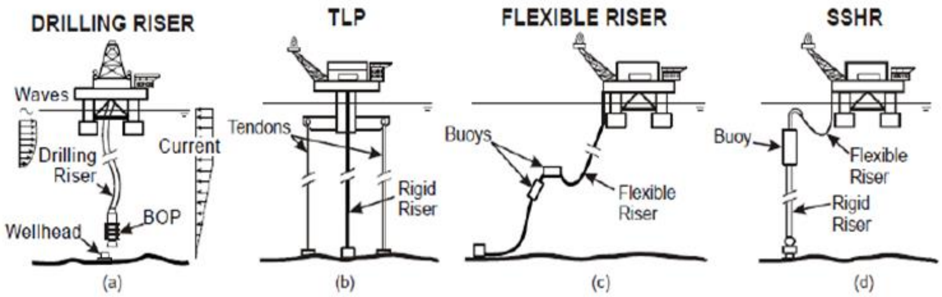

Figure 1.1 Types of riser system configurations used in oil and gas production, namely (a) free-standing riser, (b) top-tensioned risers (TTRs), (c) catenary riser (lazy-wave), and (d) hybrid riser tower, reproduced from Murai & Yamamoto (2010)

VIV is a fluid-structure interaction phenomenon that occurs when the vibration of a structure is induced by forces generated from the vortices shed off the structure, as illustrated in Figure 1.2. The vortex shedding produces the fluctuating forces, namely the lift and drag forces, which induce the cross-flow (CF) and in-line (IL) vibrations, respectively. When the vortex shedding frequency approaches the structure's natural frequency, the lock-in (synchronisation) phenomenon will occur. The peak amplitude can be observed in the lock-in region. At this moment, the body's motion controls the vortex shedding frequency in the lock-in region. The continuous high oscillating vibration amplitude can cause significant fatigue damage and shorten the fatigue life of the cylinder. The study of fluid-structure interaction phenomenon is significant for understanding to predict and avoid the VIV phenomenon in the future.

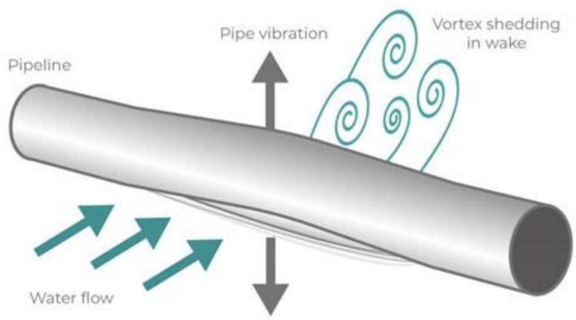

Figure 1.2 The formation of vortex shedding behind a pipeline, reproduced from ATMOS International (2022)

The use of two or more cylinders has been increased due to the growth of engineering projects for energy extraction and generation, such as marine risers for deep-sea oil exploration. Hybrid riser towers typically comprise 4 to 12 risers to transport the produced hydrocarbon fluids, as shown in Figure 1.3. By using multiple risers, operation costs and time consumption can be reduced. Not only in oil and gas operations but most structures on land and in the ocean come in multiple forms. The VIV behaviour becomes more complex when a group of cylinders is involved in the application due to the flow interference between the cylinders. Cylinders can be arranged in tandem, side by side, or staggered configurations (Huera-Huarte et al., 2016). Flow interference may affect the formation of vortex shedding in the flow. It is highly dependent on the separation distance between the cylinders, the number and configuration of the cylinders (Zdravkovich, 1988). A thorough understanding of the characteristics of fluid flow and vortex dynamics around a pair of two cylinders is crucial for having full knowledge and controlling the VIV phenomenon.

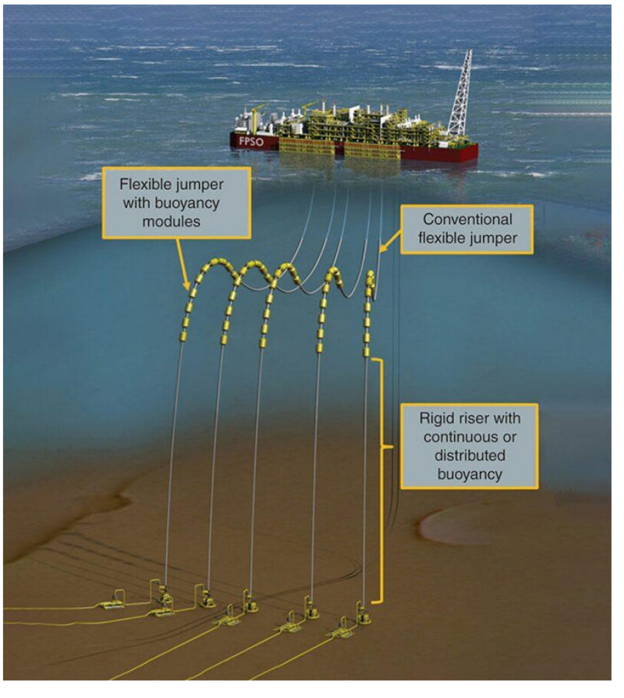

Figure 1.3 The hybrid riser tower with more than one rigid riser, reproduced from Carpenter (2020)

Furthermore, it is essential to have a particular device to control the VIV, especially for this complex structural interaction. Maintenance budgets for the riser system connecting to the hydrocarbons wells increase, forcing the industry to consider using a suppression device for the riser. Suppression of VIV has been one of the most active research topics and patenting in fluid dynamics for many decades due to its significance in engineering applications. It is critical to remove and reduce vibration to extend the riser's lifespan by reducing the fatigue damage of the structure. Vibration reduction can be obtained in various methods, which are passive, semi-active, active and hybrid. Physically, the role of vibration control is to break up the correlation vortices along the structure, which changes the structure's natural frequency and dissipates vibration energy.

Among these vibration control methods, the passive method offers a reliable and simple system at a low cost. These passive devices can be classified into two categories, namely near-wake stabiliser and surface-geometry modifier (Sumer & Fredsoe, 2006). Fairing, splitter plate, guided foil, and developed connected-C device are examples of near-wake stabilisers. Normally, that fairing installation and maintenance costs are high. Meanwhile, protrusions, grooves, and helical strakes are categorised as surface-geometry modifiers. These devices could control the boundary-layer vorticity distribution and separation points over the vibrating structure via surface variation. Helical strakes are more cost-effective and powerful options for deepwater risers.

1.2 Problem statement

The exploration of offshore oil resources moves further offshore and deeper underwater. One of the main challenges related to the deepwater field is the design of the riser system. The riser system involves either a flexible or rigid riser. Flexible risers, that are long, slender, and large in aspect ratio, are primarily employed in deepwater field development to transfer oil from the seabed to the platform. However, flexible risers still have their limitation by water depth, with currently a few installed over 5000 ft. They require a higher up-front capex and replacement cost in comparison to rigid risers' system. Moreover, flexible risers are complex structures and tend to vibrate at more vibration modes than the rigid type. Hence, the industry prefers to use hybrid risers due to increased activity in the deep and ultra-deepwater areas. Hybrid risers utilise both flexible and vertical rigid risers to mitigate the effects of strong waves and the ocean current. In addition to providing flexibility for platform connection, the combination of these two risers can withstand the high hydrostatic pressures and the vertical weight of a deepwater riser. However, they are vulnerable to VIV and unprotected against fatigue damage, particularly deepwater. It is critical to minimise the possible risk of fatigue damage caused by ocean vibration to reduce the replacement costs and maintain field service life.

Although the VIV can occur in airflows, the damage mostly occurs in the denser fluid such as water, especially in the ocean. This is because the ocean structure is designed with lower structural damping and a lower mass than those installed on land. As a result, the structure vibrates at a high amplitude, which causes fatigue damage if it vibrates for an extended period. In addition, by exposing the riser to the harsh environment of the deepwater area, the vibration of a low mass ratio riser can become much more complicated than that of a high mass ratio riser (Khalak & Williamson, 1999).

The industry's standard for hybrid user configuration is to bundle several riser pipes. Utilising two or more cylinders is preferable due to the cost and time savings associated with the operation. However, this application may result in proximity and wake interference between the cylinders if unappropriated separation distance is used. When cylinder structures are located in the wake of other structures, their dynamic responses become highly unusual compared to what would be expected if the structures were isolated. According to Sanaati (2012), multiple cylinders can cause the risk of collision between the adjacent cylinders. Therefore, most researchers are now aware of the importance of investigating the VIV behaviour of multiple cylinders. In addition, although many experimental and numerical methods are used to study the effect of the separation distance between the cylinders on VIV when using the rigid cylinder, the discussions focus exclusively on the trailing cylinder's response. Less attention is given to the leading cylinder response. Due to the paucity of information related to the mentioned matters, the effect of separation distance on cylinders is aimed to be clarified. At the same time, data on the critical separation distance for tandem configuration is still incomplete in the literature and would be useful to discover.

Recently, many researchers have conducted experiments with two circular cylinders in tandem configuration. However, the data on the dynamic responses of both leading and trailing cylinders are still scarce in the literature. Previous literature has primarily concentrated on either leading or trailing behaviour, with no detailed comparison of both cylinders. Besides, the study of leading cylinder towards VIV in the literature is mostly in a stationary state, as a basic fundamental study for the flow interference between cylinders. Although only a few studies have discussed the leading and trailing cylinders, configuration is based on the fix-vibrate or fix-fix rigid cylinder. The most recent study by Xu et al. (2018) explains the response of both oscillating cylinders, but the authors conducted the vibration experiment solely with flexible cylinders. Despite the fact that flexible cylinders have been studied, rigid cylinders also are used in real-world hybrid risers and most offshore structures. In the case of rigid cylinders, Assi et al. (2010) and Korkischko & Meneghini, (2010) only discussed the trailing cylinder response. Their trailing cylinder which is free to move was subjected to the wake of a fixed leading cylinder. There has been no study has reported on the results of both rigid cylinders in tandem configuration that are free to move in the CF direction. This could be due to the complex response of the oscillating cylinders due to the VIV and the flow interference. Since most of the risers in offshore industries are not in a fixed condition, investigating the VIV of the oscillating rigid cylinders is feasible and significant to be studied. Therefore, the novelty of this study is to explore the response of two rigid cylinders that are allowed to move in the CF direction simultaneously. For a better understanding the set-up of the cylinder in tandem configuration, an illustration of the set up-are drawn in Figure 1.4. Figure 1.4 shows the cylinders in the fix-fix configuration have been supported by the fix supported rod, which prevent them from moving in any direction. For the fix-vibrate configuration, a fix support rod is only installed at the leading cylinder, while the spring is installed at the trailing cylinder. Meanwhile, the cylinders that both allowed to move at CF direction are supported by the spring for both leading and trailing cylinders.

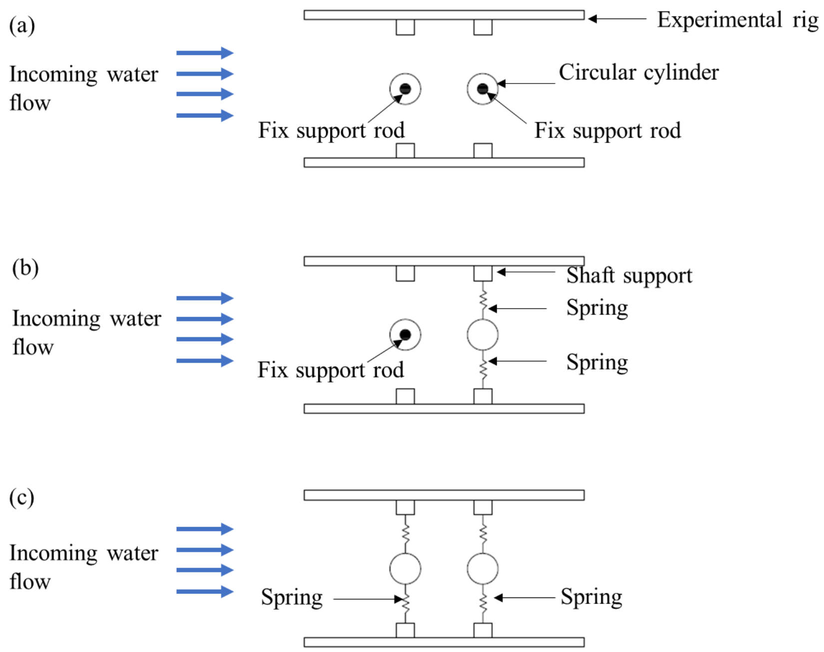

Figure 1.4 Definition sketch of different cylinder's set-up in tandem configuration. (a) fix- fix, (b) fix- vibrate, and (c) vibrate-vibrate cylinder

On the other hand, a suitable suppression device is needed to reduce the vortex shedding, leading to the fatigue damage of the risers. Helical strakes are commonly used to suppress the vibration. Most studies on helical strakes focus on the strakes' pitch and height. However, the interaction of two cylinders fitted with helical strakes receives scant attention. The relationship between a pair of rigid cylinders fitted with helical strakes is still unknown. Additional investigations into reducing the VIV of two rigid cylinders using strakes are sorely needed and warrant further exploration due to the little attention funnelled to the interaction of two cylinders fitted with helical strakes. The main problem for two cylinders in the water flow is the interference that can affect the flow characteristics around the cylinders fitted with helical strakes.

To the author's best knowledge, no study on the effects of different helical strake arrangements between the cylinders has been published in the literature for rigid cylinders in tandem configuration. In the most recent study, Xu et al. (2018) investigated the performance of helical strakes in different arrangements on the two flexible cylinders. Therefore, in the present study, the performance of helical strakes on rigid cylinders is discussed and a detailed discourse of both cylinder responses is presented. Additionally, helical strakes were tested in various arrangements at the critical separation distance determined in this study. This critical separation distance was identified during VIV testing on two bare cylinders. The current literature does not contain data on cylinder responses towards the VIV at the critical separation distance for different helical strake arrangements among the rigid cylinders. These data are crucial for offshore engineers to forecast the VIV phenomenon in a critical condition. Hence, the present study is also interested in the relationship between adjacent bare/straked cylinders towards the VIV at the critical separation distance.

1.3 Research objectives

Based on the problem statements, this research work has the following objectives:

i) To characterise the VIV response of adjacent cylinders with various separation distances through the amplitude, frequency response, spectral density analysis, and phase difference in tandem configuration.

ii) To identify the critical separation distance of VIV for two adjacent cylinders in tandem configuration.

iii) To examine the effect of helical strakes on rigid cylinders at the critical separation distance in tandem configuration.

1.4 Research scope

This research work is designed to focus on the following scopes:

a) The study only focuses on low mass ratio rigid cylinders in tandem configuration.

b) The study's variables are the separating distance and the helical strakes arrangements.

c) The cylinder is attached to the three-start helical strakes with a height of 0.15*D* and a pitch of 10.0*D*.

d) A high damping experimental rig is used.

e) Cylinders are allowed to move in a cross-flow direction only.

f) The cylinder risers are subjected to uniform flow with different speeds ranging from 0.1 to 0.58 m/s, which is within the subcritical Reynolds number range.

g) The measurements of interest are the amplitude response, frequency response, spectral density analysis, and phase difference.

h) Other properties such as water density, water temperature, water level, and turbulence intensity will remain constant.

It should be noted that there were some limitations in the experiments conducted. This present study is focused on the rigid cylinders as the test model for the riser in deepwater applications. During the experiment, small aspect ratio of the cylinder was used to ensure that the cylinder was rigid enough and fitted in the water flume. A full-scale offshore riser cannot be achieved for the purpose of the experimental work in the laboratory. Although the complex and unpredictable ocean current in real condition is unable to be reproduced in the laboratory's work, the uniform current throughout the entire structure, which is the most critical condition, is tested in the present study. Besides, the parameter of the physical system such as the mass ratio, damping and aspect ratio are implemented. As a fundamental study, the assumption in scaling the test model for the real application is by categorised the responses of the cylinder based on the parameter's range. For instance, the cylinder's responses for the parameter of aspect ratio and mass ratio should be within the specified range that has been standardised.

1.5 Significance of knowledge

- Through this research, it could help the offshore engineer in predicting a suitable separation distance for multiple risers to minimise the undesired harmful oscillation and ensure safe operation. The value of critical separation distance of multiple rigid cylinders, which contribute to a strong cylinders' oscillation is identified.
- The VIV response of multiple cylinders that free to move is successfully explored, which has yet to be discovered due to the complex response of flow interference between the cylinders.
- The study of flow interference of rigid cylinders is necessary, not only on flexible cylinders because the offshore industry today prefers to use hybrid cylinder for deepwater area that include multiple rigid cylinders in the system.
- Due to the high rate of fatigue damage of deepwater drilling riser, the suppression device is crucial to be installed in order to increase the riser's lifespan. Through this study, the effectiveness of helical strakes in reducing the cylinder's vibration is well explored on the multiple rigid cylinders, which has yet to be studied.
- The comparison between rigid and flexible cylinder is important because rigid cylinder's results have been used extensively by the offshore industry to predict the VIV performance of a long flexible marine riser.

1.6 Thesis outline

This thesis is divided into five chapters, including this chapter. The current chapter lays the introduction to the thesis and an overview of the research background. The outline of the research problem is briefly described in detail. This chapter also outlines the objectives, scopes, significance of knowledge, and thesis structure.

In **Chapter 2**, a thorough review of the available related research studies is provided. This chapter starts with introducing vortex-induced vibration (VIV). It includes a review of the important parameters for the VIV analysis and the phenomenon of vortex-induced vibration on a single cylinder. The following section contains the study of VIV on multiple cylinders, which mainly focuses on the cylinders in the tandem configuration. The previous literature findings regarding the separation distances between the cylinders are discussed to determine the suitable values to be implemented in this research. The final section reviews the study of VIV using suppression devices such as the helical strake.

Chapter 3 details the experimental design and set-up of the present study. The experiment was conducted using a water flume at the National Hydraulic Research Institute of Malaysia (NAHRIM). All equipment needed in the experiment is addressed and the schematic diagram of the test rig set up is displayed. A new experimental rig is designed, and this mentioned process takes months to complete. The measurement techniques are explained in detail. This chapter also described the free decay test to obtain the natural frequency of the cylinder and the damping value. Lastly, a discussion on the result of the response of a single rigid cylinder is presented. A detailed comparison was made using the previous study data to validate the experimental method. This chapter also describes the VIV characteristics to understand better how a rigid cylinder will behave in terms of amplitude, frequency response, and spectral density analysis.

Chapter 4 elaborates the discussion of flow interference between two rigid cylinders in tandem configuration at different separation distances. The results of the amplitude, frequency response, spectral density analysis, and phase difference have been presented and discussed. This chapter will also identify the critical separation distance between the cylinders, which will be one of the main focuses. Comparison with the straked cylinders' case has been made to evaluate the performance of helical strakes in reducing the vibration of the cylinder. The evaluation has been performed at the critical separation distance determined through the bare cylinders' case. Different arrangements of helical strakes have been used for the cylinders in tandem to determine the effectiveness of the helical strakes. The straked cylinders are measured using the same techniques as the previous tests.

Finally, **Chapter 5** summarises the main findings and contribution of the present study. Recommendations for future work are also made to suggest the potential investigations of the present study.

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LIST OF PUBLICATIONS

This work has been disseminated through the following publications.

Published Journal:

- **Sukarnoor, N.I.M.**, Quen, L.K., Abu, A., Kuwano, N., Kang, H.S. & Safari, M.D. (2022). The Effectiveness of Helical Strakes in Suppressing Vortex-induced Vibration of Tandem Circular Cylinders, *Ain Shams Engineering Journal, 13*(1), 101502

- **Sukarnoor, N.I.M.**, Quen, L.K., Abu, A., Kuwano, N., Kang, H.S. & Safari, M.D. (2022). Investigation on the dynamic behaviour of two rigid cylinders in tandem arrangement under vortex-induced vibration. Submitted to *Journal of Ocean Engineering and Science, In Press,* Available Online 31 May 2022

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