Numerical Modelling and Global Response Assessment of Floating Docks towards Efficient, Safer and Autonomous Docking Operations

by

Jianan Zhang

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University of Stavanger
NO-4036 Stavanger
NORWAY
www.uis.no

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Preface

This thesis is submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy (PhD) at the University of Stavanger (UiS), Norway. The research work has been carried out at the Faculty of Science and Technology, Department of Mechanical and Structural Engineering and Materials Science, in the period from July 2021 to May 2024. The main supervisor was Prof. Muk Chen Ong, and the co-supervisors were Assoc. Prof. Lin Li and Dr. Xueliang Wen. The PhD project was funded by POLNOR EEA and Norway Grants.

I confirm that this thesis is my own work and I have documented all sources and material used.

Stavanger, Norway
February 13, 2024

Jianan Zhang

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Abstract

Floating docks are known for their construction efficiency and operational flexibility compared to traditional graving docks. They play an important role in shipyards by serving as essential platforms for vessel construction, maintenance, and repair. Docking a vessel relies on precise ballasting and de-ballasting operations for achieving the desired floating position of the floating dock. Traditionally, these tasks are manually performed by skilled dock masters who regulate ballast valves and pumps. The entire vessel-docking operation takes hours, and the motions of the floating dock and vessel are slowly and steadily. However, the floating dock and vessel are still facing safety challenges during operations. According to the reported accidents occurring in floating dock operations, malfunctions of the ballast water system, overloading and improper ballast control are the main threats to the stability and structural integrity of the floating docks. To address these concerns and enhance operational safety, a thorough response assessment of vessel-docking operations is important. This thesis focuses on developing an in-house code to facilitate a comprehensive global response assessment of a full-scale floating dock, aiming to enhance overall operational safety and efficiency.

The in-house code is developed under a quasi-static assumption and enables dynamic, stability and global structural response assessments of various types of floating dock operations. Multiple numerical tools are incorporated into this code. Various loads applied to the floating dock and vessel are determined using the numerical tools: a hydrostatic force model, a hydrodynamic force model, a mooring force model, and a contact force model. Within the load calculations, the dock-vessel coupling loads are highlighted, including contact loads between the docking blocks and the docked vessel and the loads attributed to the mooring ropes between the dock and vessel. A six-degree-of-freedom (6-DOF) model is developed to determine the motions of the dock and

vessel based on the obtained loads. In the 6-DOF model, the dock and vessel are represented as rigid bodies with six degrees of freedom. The ballast piping network of the floating dock is modelled in a hydraulic model for the ballast water system. The flow rates into or out of all ballast tanks are computed for updating the ballast water volumes due to ballast water adjustment. Furthermore, a modified proportional controller (P-controller) is introduced to achieve automatic ballast water control, regulating opening angles of ballast tank valves to minimize roll and pitch motions during vessel-docking operations. The developed numerical tools are verified against theoretical models and various commercial software. They are also validated through experimental tests on a model-scale floating dock.

The motions and loads obtained from the dynamic analysis of floating dock operations are important inputs for stability and structural response assessments. The curves of metacentric height and righting arm are obtained using dock motions, hydrostatic loads, and the coordinates of the dock's centre of gravity (CoG) and centre of buoyancy (CoB). For structural response assessment, a bending model is proposed to evaluate the global bending deformation of the floating dock based on the applied loads obtained from the dynamic analysis. This deformation is also fed back to the dynamic analysis to update the applied loads and motions of the floating dock and vessel.

The proposed numerical tools have practical applications in the floating dock's design, maintenance and operations. The dynamic processes of gravitational ballasting for the maintenance of a floating dock are investigated. Effective tank valve status arrangements are designed for lifting different parts of the floating dock out of water for inspection. Simulations of ballasting and de-ballasting operations for a single floating dock demonstrate the reliable performance of the automatic ballast control algorithm in minimizing the roll and pitch of the dock. Moreover, the control performance of the proposed automatic ballast control algorithm is examined during de-ballasting operations

with a malfunctioning pump. The importance of using mitigation measures and smart ballast control strategy is highlighted. Finally, the vessel-docking operations considering the automatic ballast control and global deflection of the dock are studied. The dock's motions and deflections are computed using two methods: one-way and two-way couplings between the dock's deformation and motions. The maximum roll and pitch angles obtained using the two methods are close to each other, maintained below 0.13deg and 0.04deg, respectively, which indicating a robust control performance of the proposed automatic ballast control algorithm.

List of Publications

List of research papers presented in this thesis

Paper 1

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Paper 2

Zhang, J., Ong, M. C., Wen X. (2024). A Numerical Model for Stability and Dynamic Analyses of a Floating Dock during Operations. *IEEE Journal of Oceanic Engineering*. (Under review)

Paper 3

Zhang, J., Wen, X., Kniat, A., Ong, M. C. (2024). A comparative analysis of numerically simulated and experimentally measured static responses of a floating dock. *Ships and Offshore Structures*, 1-18.

Paper 4

Wen X., Zhang, J., García Conde, A., Ong, M. C. (2023). Numerical study on the automatic ballast control of a floating dock. *Journal of Offshore Mechanics and Arctic Engineering*, 146(4), 041401.

Paper 5

Zhang, J., Ong, M. C., Wen, X. (2024). Dynamic analysis of the de-ballasting operation of a floating dock with a malfunctioning pump. *Journal of Marine Science and Application*. (Accepted)

Paper 6

Zhang, J., Ong, M. C., Wen, X. (2024). Dynamic and structural analyses of floating dock operations considering dock-vessel coupling loads. *Ocean Engineering*. (Under review)

List of research papers not presented in this thesis

Paper 1

Zhang, J., Liu, Z., Ong, M. C., Tang, W. (2022). Numerical Simulations of the Sliding Impact between an Ice Floe and a Ship Hull Structure in ABAQUS. *Engineering Structures*, 273, 115057.

Paper 2

Zhang, J., Wen, X., and Ong, M. C. (2023). Development of a floating dock numerical model and the ballast water distribution strategy. In ASME 2023 42nd International Conference on Ocean, Offshore and Arctic Engineering, Melbourne, Australia. 86878, V005T06A068.

Paper 3

Wen, X., García Conde, A., Zhang, J., and Ong, M. C. (2023). Numerical Study on the Automatic Ballast Control of a Floating Dock. In ASME 2023 42nd International Conference on Ocean, Offshore and Arctic Engineering, Melbourne, Australia. 86878, V005T06A067.

Paper 4

Zhang, J., Wen, X., Ong, M. C. (2023). Numerical study on the de-ballasting operation of a floating dock with a malfunctioning pump. In *IOP Conference Series: Materials Science and Engineering*, 1294(1).

Paper 5

Wen, X., García Conde, A., Zhang, J., Ong, M. C. (2024). Dynamic Analysis of a Floating Dock under Accidental Conditions. *Applied Ocean Research*, 144, 103908.

Paper 6

Wen, X., Zahi, T., Zhang, J., Ong, M. C. (2024). Dynamic Analysis of Floating Dock Operations with Corrosion-induced Holes at Ballast Tanks. *Journal of Ship Research.* (Under Review)

Paper 7

Wen, X., Zhang, J., Ong, M. C., Kniat, A. (2024). Comparative Study of Numerical Modelling and Experimental Investigation for Vessel-Docking Operations. *Marine Structures.* (Under Review)

Contents

1 Introduction

1.1 Research Background and Motivation

The number and size of new vessels have risen sharply in recent years. In order to keep up with the demand for new vessels, dry docks are built by the shipyards to increase their capacities for ship construction, repair and maintenance (Warnke, 1975). A dry dock is a narrow basin or vessel, which can be flooded to allow a vessel to be floated in, and then drained to allow that vessel to rest on a dry platform. There are two main types of dry docks: graving docks and floating docks.

A graving dock is a traditional form of dry dock. Figure 1.1 shows a photograph of ‘Dry Dock No.1’ located at the Norfolk Naval Shipyard in Portsmouth Virginia, built at early 1830s. It is the oldest operational dry dock facility in the United States and still regular in use (Virginia Department of Historic Resources).

Figure 1.1 Norfolk Naval Shipyard: Dry Dock No.1 located at the in Portsmouth, Virginia (Detroit Publishing Co, ca. 1905).

Figure 1.2 shows its sister facility located at Boston Harbor, which is closed off and maintained empty and dry since 1974. As shown in Figure 1.2, a graving dock is a fixed basin built into the ground near the sea (Sadeghi et al., 2018) and closed by gates. When the gates are opened, a vessel is floating inside the dock. Then, the gates are closed, and the water is pumped out, leaving the vessel supported on the docking blocks for being inspected or serviced. Nowadays, the gates are usually made of steel and concrete to seal the dock and prevent water from flowing into the dock during the maintenance or repair of the vessel (Wankhede, 2021). Graving docks used for navy vessels may be built with a roof, to prevent spy satellites from taking picture of them. Another benefit of the covered graving docks is that weather condition nearly has minimal influence on the work. Consequently, the risk of delays in vessel building or repair is significantly reduced compared to the uncovered docks.

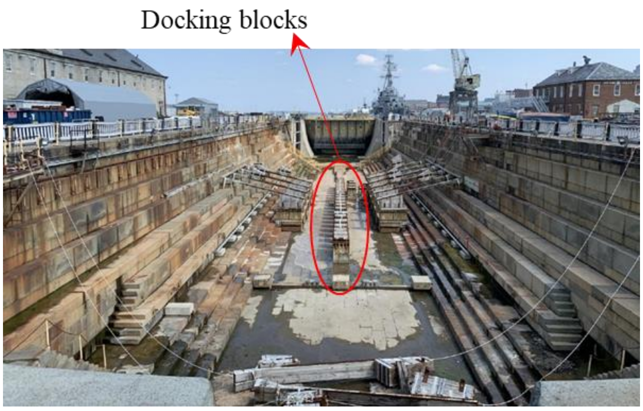


Figure 1.2 Charlestown Navy Yard: Dry Dock No.1 (Sullivan, 2021).

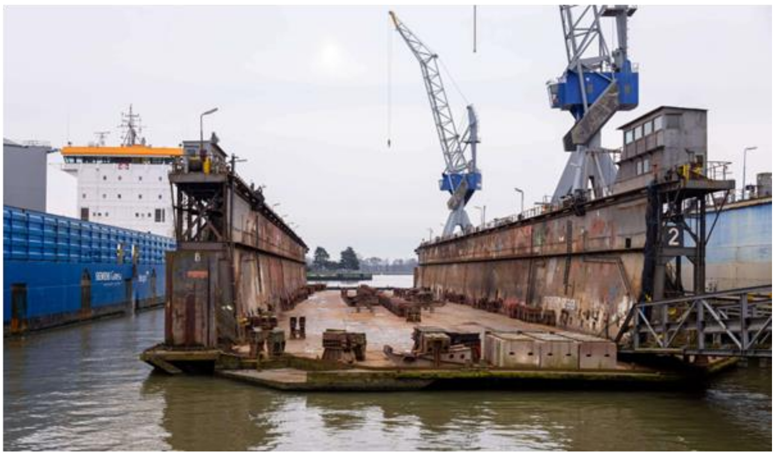
A disadvantage of the graving docks is that their functionality highly depends on the dock gates. Any problem with the gates, such as leakage and difficulties in opening or closing the gates, can cause the dock nonoperational (Budianto, 2018). Additionally, constructing graving docks occupies large area on land and requires high construction cost (Tukan et al., 2020).

In recent years, floating docks become an alternative to the graving dock due to the efficiency in constructions and flexibility in operations, since the floating docks are commonly operated in sheltered harbors, not occupying the space on land. They can also be moved to wherever they are needed. As shown in Figures 1.3(a)-(d), a floating dock is designed in a "U" shape, with a pontoon as the bottom horizontal part and two wing walls as the vertical sides. Multiple ballast tanks are equipped inside the pontoon and two wing walls. Moreover, comprehensive facilities (such as control room, cranes, electrical devices and machinery) are equipped inside the wing walls. Emptying and filling of the ballast tanks are critical to adjust the dock's draughts and minimize its heel and trim when docking and undocking the vessels. The floating dock is anchored to the seabed using mooring lines (Figure 1.4 a), and the docked vessel is tied to the dock using mooring ropes (Figure 1.3 a). There are also docking blocks between the dock and the vessel for supporting the vessel, as shown in Figure 1.4(b).

(a)

https://www.myklebustverft.no/

(b)



https://www.damen.com/services/damen-trading/used-vessels/floating-dry-dock/drydock-ship-07768

(c)

https://hegerdrydock.com/portfolio/bae-ship-repair-san-diego-capride-of-california-poca-55000-lt-capacity/

(d)

https://www.sedefshipyard.com/en/

Figure 1.3 Photos of floating docks.

(a) (b)

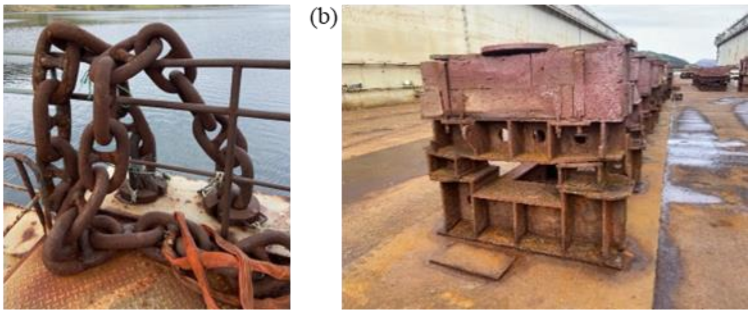


Figure 1.4 Photo of (a) mooring lines and (b) docking blocks of the floating dock at Myklebust Shipyard, Gursken, Norway.

1.1.1 Challenges to floating dock operations

Dry-docking is a commonly used procedure for the inspection, repair and maintenance of vessels, which is essential for maintaining the safety, reliability and efficiency of the vessels. The procedures of docking a vessel are demonstrated in Figure 1.5, and described as follows (Rajewski, 2018).

(a) A floating dock submerges to a maximum draught required in the docking plan by ballasting.
(b) A vessel is brought into the dock by tugboats and tied to the dock using mooring ropes when the vessel floats above the docking blocks.
(c) The floating dock is lifted by de-ballasting until the vessel's stern touches the docking blocks.
(d) The de-ballasting continues until the vessel rests on the dry pontoon deck.
(e) The de-ballasting stops until the floating dock emerges to its working position.

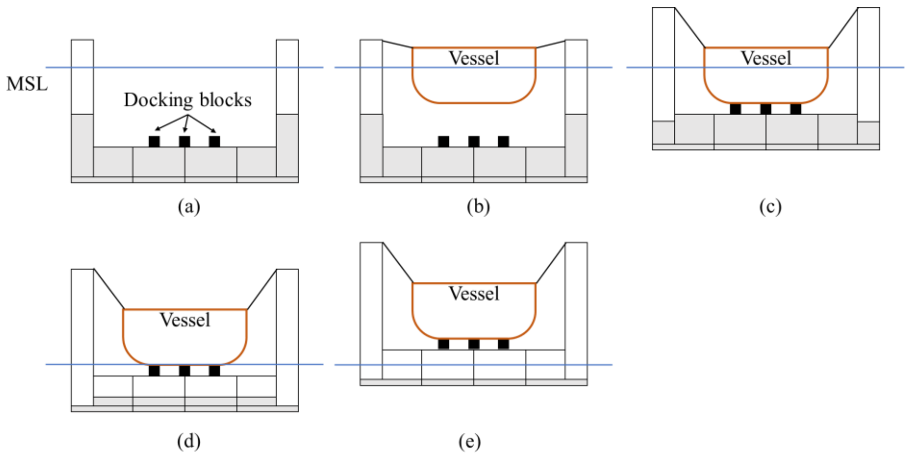


Figure 1.5 Illustration of a vessel docking operation.

The ballasting and de-ballasting operations involve filling and emptying sea water in the ballast tanks and transferring water among them to achieve the desired floating position of the dock. These tasks are typically carried out manually by a skilled dock master through regulating ballast valves and pumps. The docking process lasts for hours, and the dock and the vessel move slowly and steadily. However, potential risks still exist during the operational conditions.

In recent years, some reported accidents during the docking operations are summarized by Zhang et al. (2022), as shown below:

- December 2023: A 145-metre floating dock sank while bringing a yacht into the dock at Yachtley shipyard, Turkey. It was probably caused by the cranes rolling down their tracks (The Maritime Executive, 2023).
- April 2019: At the Tuzla Ship Repair Yard in Turkey, a floating dock with two ships inside broke into two parts, and two cranes of the dock collapsed. The reason for the accident might be overloading, that is, the weight of the two ships exceeding the dock's lifting capacity (Voytenko, 2019).
- October 2018: 'PD-50' is a 330-metre-long and 79-metre-wide Russian floating dock. It sank while the Russian aircraft carrier Admiral Kuznetsov was aboard after a power outage of the ballast pumps. One large crane fell on the docked aircraft carrier, tearing a hole of up to 5 meters (Rainsford, 2018).
- September 2018: Aft section of Floating Dock No.169 collapsed during surfacing with two ships inside Slavyanka Port, Primorye Russia, Japan sea. Starboard tower crane fell onto tower deck, crane operator sustained slight injuries (Voytenko, 2018a).
- August 2018: A 82-metre floating dock at a shipyard in Hirtshals Harbour, Denmark, has dramatically tilted with a fishing boat inside (Olsen and Bringslid, 2018).

- January 2018: The floating dock SSR-1 tilted and partially rested on the bottom at Ship Repair Yard in Szczecin, Poland (Voytenko, 2018b).
- April 2017: A small floating dock suddenly rolled about 70 degrees with the “Hordafor V” tanker ship on deck in Nauta shipyard in Gdynia, Poland. The floating dock had lost stability and rolled over on its side, spilling the tanker into water (Landowski, 2017).
- March 2015: At the Remontowa Yard in Gdansk, Poland, the ferry ship Prinsesse Benedikte slipped down from the keel blocks due to an excessive heeling of the dock (Schuler, 2015).
- March 2012: In Vigor Industrial Shipyard, Port of Everett, Washington, a malfunctioning valve of the Dry Dock #3 caused the flooding of the ballast water tank and listing of the dock. This accident ended up with the sinking of the dock and the docked ship. (National Transportation Safety Board, 2013).

These accidents indicate that stability loss and structural damage are the main safety issues for floating docks. Many potential risks during operational conditions are the initiating factors for the accidents, which are discussed below:

(1) Malfunctions of the ballast water system

The ballast water system includes ballast pumps, valves, pipes, and ballast tanks (David, 2015). Its sound operation is crucial for ensuring the adequate buoyancy and stability of floating docks during docking operations. Inadequate maintenance of the ballast water system has a great potential to result in accidents (Gul et al., 2017).

The ballast pumps are crucial for pumping sea water in or out of the ballast tanks and balancing the floating dock during most of the operational conditions. Therefore, the functionality of the floating docks highly depends on the sound operation of the ballast pumps (Kimera and Nangolo, 2020). The malfunctioning ballast pumps can cause imbalanced weight distribution of the dock and increase the risk of capsizing. Since the ballast pumps normally rely on electrical power during operations, the fault in electrical supply, such as power outages (Rainsford, 2018) and overloaded motors (Kimera and Nangolo, 2020), can cause the failure of pump operations. Moreover, the solid particulates in the sea water passing through the pumps can damage the mechanical system of the pumps (Wang and Qian, 2017).

The ballast valves also play an important role in the floating dock operations since the ballast water adjustment relies on the regulation of the openings of the valves. Any malfunction of the ballast valves may have an adverse impact on the flow in or out of the dock and among the ballast tanks (National Transportation Safety Board, 2013). Consequently, the floating dock may have uneven distribution of the ballast water, flooding of ballast tanks, and excessive trimming or listing within a short time.

Moreover, the corrosion of the ballast tanks can also impact operational safety of the floating docks. The corrosion of the ballast tanks can result in loss of local or global structural strength or fatigue failure (De Baere et al., 2013).

(2) Overloading

Floating docks are subjected to heavy loads resulting from their own weight and the docked vessels. Due to the increasing sizes of modern vessels (Kaukiainen, 2012), the floating docks are required to be designed with larger lifting capacity. The contact loads resulting from the weight of the docked vessel and the subsequent deformation also increase. By 2014, the largest floating dock in the United States, known as the Vigorous drydock, was 292.6-metre-long with a lifting capacity of

80,000 tons (Schuler, 2014). In the largest shipbuilding nations, such as South Korea, China and Netherlands, largest floating docks can exceed 400 meters long (Kaup et al., 2018).

The dock may suffer from severe structural damage, if the docked vessel's weight exceeds the dock's lifting capacity and the dock's deformation exceeds the allowable range. The severe consequence of overloading is shown in Figure 1.6, where two vessels were inside the floating dock at the Tuzla Ship Repair Yard in Turkey. Moreover, it is common to adjust the ballast water distribution to compensate for the deformation caused by the docked vessel (Yoon et al., 2020).

Figure 1.6 A floating dock with two ships inside broke in two at the Tuzla Ship Repair Yard in Turkey (Voytenko, 2019).

(3) Improper ballast control

Ballast control is crucial for the stability of the floating dock during operational conditions. Currently, the ballast control is mainly performed manually by a skilled and experienced dock master, who must handle numerous ballast tanks and valves simultaneously. However, this task is challenging. Even minor mistakes can result in significant stability loss for both the dock and the docked vessel. The reason is that the floating dock's stability is sensitive to any unplanned weight shifts or incorrect ballast water adjustment due to the marginal reserve buoyancy of a submerged floating dock (Insurance Marine News, 2019). Any improper decision of the ballast control may cause severe stability loss, such as the capsizing of the floating dock and the docked vessel, as well as the loss of lives.

Based on the analysis of reported accidents and identified operational risks, the floating docks are facing safety challenges during the operations. A potential solution is developing a digital twin for vessel-docking operations. The digital twin allows real-time monitoring of dock and vessel status, predicting responses to ballast control and dock malfunctions. It can enhance operational safety and assist decision-making for the dock masters (West et al., 2021). Moreover, an automatic ballast control strategy is essential for the efficiency of ballast water adjustment during vessel-docking operations. The digital-twin solution will be detailed in Section 1.1.2, and the studies on the automatic ballast control will be presented in Section 1.1.3.

1.1.2 A Digital-twin solution

A digital twin is a digital representation of a physical object, based on sensor data and high-fidelity simulations (Brewer et al., 2019). It can describe the current state of the physical object and also predict the future state (Wang et al., 2021). Additionally, by detecting potential problems, it can provide optimization strategies for intelligent decision-making (Liu et al., 2021).

The digital twin has been applied to a wide range of industries, including manufacturing and process improvement (Javaid and Haleem, 2023; Lu et al., 2020; Wang et al., 2021), construction (Opoku et al., 2021), vehicles (Glaessgen and Stargel, 2012), healthcare (Liu et al., 2019), and urban planning (Schrotter and Hürzeler, 2020). Recently, the digital twin has been used for offshore structures. For example, Moghadam and Nejad (2022) presents a digital twin condition monitoring approach for drivetrains on floating offshore wind turbines. Sivalingam et al. (2018) proposes a novel methodology to predict the remaining useful life of an offshore wind turbine power converter based on a digital-twin framework. VanDerHorn et al. (2022) proposes a digital-twin approach for monitoring and predicting vessel-specific fatigue damage. Fang et al. (2022) proposed a fatigue crack growth prediction method based on digital twin. Based on previous research, the digital twin also has great application potential in the response assessments for the floating docks.

The construction of a digital twin includes modelling, data fusion, data interaction and collaboration, and service (Tao et al., 2018; Wang et al., 2021). Therefore, it is crucial to monitor the real-time responses of the floating docks during operational conditions. Recent advances in sensor application can be adopted. For instance, Korotaev et al. (2016) developed a real-time measuring system using camara-based devices to obtain a floating dock's deflection. Laboratory tests and field tests on a real dock indicated that the developed system demonstrated good measurement accuracy. Yang et al. (2013) proposed a deflection and inclination measuring system for a floating dock based on the connected liquid-filled pipes. The proposed measuring system was also validated by field tests. The dock's draught and ballast water levels are typically measured using pressure and level transmitter (Drwięga et al., 2017; Golz et al., 2016). Moreover, the fibre-optic strain sensors have been widely used for floating structures, such as ships (Wang et al., 2001), underwater vessels (Hsu et al., 2020), floating wind turbines (Ma et al., 2024), and offshore platforms (Ren et al., 2006).

For implementing the digital twin, a comprehensive numerical model for floating dock operations is also required. The studies on the modelling and analysis of floating dock operations will be reviewed and discussed in Section 1.2. Then, the results obtained from the numerical model of the floating dock needs to be collected (Uhlemann et al., 2017b) and integrated with the real-time data (Uhlemann et al., 2017a).

1.1.3 Automatic ballast control

As presented in Section 1.1, the ballast control of a floating dock mainly relies on manual operations. To reduce human error and improve the safety and efficiency of the ballast control, an automatic ballast control algorithm is necessary. Additionally, implementing this system on a floating dock is useful for training staff and can thus reduce associated training costs for the shipyards.

In recent decades, researchers have explored ballast control methods for different types of floating structures. Woods et al. (2012) proposed a hybrid-proportional-derivative-condition-based (HPDCB) controller to control the depth and pitch of the Autonomous Underwater Vehicles (AUVs). Kusuma (2017) designed a ballast control system for a catamaran ship using a Programmable Logic Controller (PLC) to increase the ship's stability. Bara et al. (2012) developed a ballast control strategy for a ship to optimize the ballasting procedures and reduce energy consumption.

Studies on the automatic ballast control during floating dock operations are usually combined with experimental tests. Ohkawa et al. (1984) proposed proportional controllers (P-controllers) and proportional-integral controllers (PI-controllers) to regulate the ballast valve opening angles for controlling the heel, trim and draught of a floating dock within allowable ranges. The proposed control algorithm was verified by simulations and validated against experimental tests on a real floating dock. Guo et al. (2014) designed an automatic control system for a real floating dock, using the software CP400Soft developed by ABB Group (2010). The system regulates the opening angles of 30 ballast pumps and the on and off of four pumps. The dock's draughts at four corners, ballast water levels, and deflection are monitored using sensors and fed back to the control system. Moreover, if the automatic control system encounters a failure, the manual control could take over. Similarly, Topalov et al. (2018) proposed a Supervisory Control and Data Acquisition (SCADA) system for the automatic ballast control of a floating dock. The controller's feedbacks are the dock's heel, trim and deflection, and the output is the status of four ballast pumps and 18 valves.

The development of these automatic ballast control algorithms relies on the sensor data obtained from real floating dock operations. However, field test measurements are expensive and time-consuming, and the consequences of control system failure are severe, such as the sinking of the dock, injuries, and even deaths. To prevent such failure and reduce cost, numerous numerical simulations should be performed to test the control performance before conducting the experiments. Additionally, the control performance under malfunctioning ballast water systems should also be examined to improve the performance of the automatic ballast control algorithms.

1.2 Modelling and Analysis of Floating Dock Operations

In order to predict the real-time responses of the floating dock for the digital twin, comprehensive numerical analyses are required. Since stability loss and structural damage are the main safety issues for floating dock operations, researchers focus on the stability and structural response analyses of the floating docks.

1.2.1 Stability and structural responses based on static analyses

Following DNV guidelines (DNV, 2015), researchers in recent years perform stability and structural response assessments based on static analyses under several critical loading conditions (Zhang et al., 2022), including:

- Submerged to minimum freeboard;
- Immersed just below the top of docking blocks;
- Final working condition.

The docked vessel is considered in sagging and hogging conditions with symmetrical weight distributions on the docking blocks. For determining the stability of a floating dock, the metacentric height ($\overline{\mathrm{GM}}$) and righting arm ($\overline{\mathrm{GZ}}$) are critical parameters, typically calculated using the dock's hydrostatic characteristics, such as centre of gravity (CoG), centre of buoyancy (CoB), and metacentric radius (Kodathoor Gangadharan, 2009; Njumo, 2017; Sasono et al., 2018). Sundaresan et al. (2017) used NAPA software to calculate hydrostatic curves and studied the stability in five docking phases, finding significant loss in stability when sea level just exceeded the pontoon deck. Sasono et al. (2018) and Kodathoor Gangadharan (2009) modelled dry docks using MAXSURF software, considering the corrections of $\overline{\mathrm{GM}}$ due to the ballast water's free surface effect. Despite the widespread use of commercial software like MAXSURF and NAPA for the stability analysis of floating structures, these tools have certain limitations. One limitation is their potential incompatibility with other numerical tools, making it challenging to integrate them into other numerical tools such as the digital twin models for industrial purposes. Additionally, the implementation of these tools can be hindered by their high licensing costs.

Previous numerical studies on the structural response assessments of floating docks are also based on static analyses, similar to the stability calculations. Burlacu and Domnişoru (2019), Burlacu et al. (2017) and Dankowski and Weltzien (2017) modelled the floating docks as one-dimensional (1-D) beam models. Moreover, the floating docks were modelled as three-dimensional (3D) finite element models by El-Maadawy et al. (2018), Burlacu and Domnişoru (2018), and Guan et al. (2018). Some assumptions are adopted when calculating the contact loads due to the docked vessel and ballast water. The contact loads are assumed constant and simplified as either a sagging or hogging ship. The weight of the ballast water is uniformly distributed along the longitudinal direction of the dock (Burlacu and Domnişoru, 2018; Burlacu et al., 2017).

It can be concluded that the stability and structural calculations based on static analyses fail to ensure overall safety throughout the operations, or meet the requirements of the digital twin model due to the following aspects:

- The static analyses can only provide the dock's responses under limited loading conditions. However, the digital twin model requires real-time simulations for the entire docking operation.
- The accuracy of modelling the ballast water system and loads applied to the floating docks needs to be improved. The assumptions and simplifications in the static calculations may impact the reliability of the obtained responses. However, the digital twin requires high accuracy (Wright and Davidson, 2020) in predicting the behaviour of the floating dock.
- The static analyses cannot be adopted to test the automatic ballast control algorithm.

Alternatively, conducting dynamic analyses of floating dock operations can address the deficiency of the static analyses by handling various dynamic loads applied to the dock, providing time-domain results, enabling testing the automatic ballast control algorithm, and thus contribute to the development of the digital twin.

1.2.2 Modelling the loads applied to the floating docks for dynamic analyses

Utilizing the equations of motion in the time domain can be promising to determine the dock's dynamic responses. The accuracy in the modelling of the time-varying loads applied to the dock is crucial for the reliability of the dynamic responses. The floating docks experience complex external loads during operations, such as environmental, hydrostatic, hydrodynamic, mooring, and the coupling loads between the dock and the docked vessel.

(1) Environmental loads

Different from most offshore structures, floating docks are typically located in a sheltered area and are not exposed to significant waves. However, floating docks may be subjected to strong wind loads at specific geographical locations and under certain weather conditions. The cranes and other machinery positioned high on the wing walls makes the floating dock and the docked vessel prone to the risk of toppling over during a gust of wind (Insurance Marine News, 2019; Zhang et al., 2022). To avoid such consequences, shipyards carefully choose the timing of docking operations, and docking operations are typically scheduled during periods with minimal environmental loads. Therefore, the environmental loads can be ignored when simulating floating dock operations.

(2) Hydrostatic loads

The hydrostatic forces and moments generated by the dock's displaced water and ballast water. Traditional hydrostatic calculations typically focus on the restoring force resulting from buoyancy and the gravitational force acting on a floating structure (Faltinsen, 1993). However, this approach presents limitations in floating dock operations due to the dock's changing draught, heel, and trim over time. The hydrostatic loads due to ballast water vary with the dock's floating position and ballast water distribution among the ballast tanks. It is imperative to calculate hydrostatic loads accurately at any given floating position. Additionally, ballast water volumes are adjusted throughout operations, highlighting the importance of properly modelling the complex ballast water system (Elidolu et al., 2023) and accurately calculating flow rates.

(3) Hydrodynamic loads

The added mass and damping loads are steady-state hydrodynamic loads due to the forced rigid-body motions (Faltinsen, 1993). Potential flow solvers are widely used for calculating the added mass and damping coefficients of the floating structures. Frequency-dependent added mass and damping coefficients can be calculated from software like WAMIT (WAMIT, 2023) and WADAM (DNV, 2017). However, this method has limitations when considering floating dock operations. As the dock's draught changes during operation, calculating hydrodynamic coefficients for each draught becomes necessary. However, this process demands significant computational resources and is time-consuming. Hence, an efficient method is necessary to calculate the dock's hydrodynamic loads for the real-time simulations of the digital twin model.

(4) Mooring loads

The floating docks and the docked vessel are moored using mooring lines and mooring ropes, respectively. The mooring loads should be considered for both the dock and the vessel. Mooring system can be modelled in different manners. Finite element model (Aamo and Fossen, 2001) (Buckham et al., 2004) (Kim et al., 2013) and lumped mass model (Masciola et al., 2014) (Hall and Goupee, 2015) are commonly used for calculating the dynamic responses of the mooring lines. These methods provide accurate result but require significant computational resources.

For many applications, such as modelling mooring lines attached to a vessel, the interest lies in the reaction forces acting on the vessel and the details of mooring forces within lines are unnecessary. Thus, a realistic approximation can be adopted (Orcaflex), such as the quasi-dynamic analysis and quasi-static analyses, recommended by classification societies including Bureau Veritas (BV, 2021). Analyses can be performed using codes including ARIANE (Chrolenko, 2013), SESAM Mimosa (Shafieefar and Rezvani, 2007), and MAP++ (Cottura et al., 2021), based on the classical analytic catenary equations (Faltinsen, 1993) are used in these analyses (Orcaflex).

(5) Contact loads

As mentioned in Section 1.2.1, the static analyses simplify the contact loads as a hogging or sagging ship. However, during the docking operations, the docked vessel gradually contacts the docking blocks, and thus the contact loads are dynamic. The arrangement and material properties of the docking blocks are important for modelling the contact loads. The docking blocks, made of steel at the bottom and wood at the top, can be modelled as non-linear springs (Dankowski and Weltzien, 2017).

In conclusion, the loads applied to floating docks differ significantly from those applied to vessels and other offshore structures. Therefore, a novel numerical model is necessary for floating docks, which considers ballast water adjustments and interactions between the dock and the docked vessel.

1.3 Research objectives

This thesis aims to set a starting point for the dynamic analyses of floating dock operations and to contribute to safer, efficient and autonomous docking operations. The thesis deals with the development of numerical tools for a comprehensive global response assessment of a full-scale floating dock. The developed tools are employed to perform dynamic analyses for the ballasting and de-ballasting operations of a single floating dock, along with the vessel docking operations. In particular, the following sub-objectives have been defined and achieved:

(1) To establish the framework of a comprehensive global response assessment tool for docking operations, including dynamics, stability, and structural responses.

(2) To develop numerical tools for analyzing loads applied to a floating dock and a vessel during operations. The dock-vessel coupling loads should be highlighted and the interaction between the dock's structural response and motions is addressed.

(3) To model the ballast water system of the floating dock and propose an automatic ballast control algorithm to minimize roll and pitch of the dock during operations.

(4) To investigate dynamic responses of the floating dock during normal operations and accidents of ballast system malfunctions.

(5) To verify and validate the developed numerical tools in the present study against various commercial software and experimental tests.

1.4 Thesis Structure and Declaration of Authorship

The thesis consists of six chapters. A brief description of each chapter is shown below:

Chapter 1: The first chapter overviews the background, motivation, objectives and outline of the thesis. The purpose for modelling the floating dock operations, and the available methods for the global response assessments are discussed.

This chapter is partly published as:

Zhang, J., Li, L., Ong, M. C., El Beshbichi, O., and Kniat, A. (2022). Development of a Response Assessment Tool for a Floating Dock System. In ASME 2022 41st International Conference on Ocean, Offshore and Arctic Engineering, Hamburg, Germany. 85901, V05BT06A014.

The PhD candidate is the first author of the paper, contributed to the work conceptualization, conducted literature study, performed numerical simulations, post-processed the results, and wrote the main manuscript. The co-authors, Dr. Lin Li, and Prof. Muk Chen Ong, contributed to the work conceptualization, provided comments on the manuscript draft, supervision, and discussion of the results. The co-authors, Dr. Omar El Beshbichi and Dr. Aleksander Kniat, provided comments on the manuscript draft.

Chapter 2: The second chapter presents the development of global response assessment tools for floating dock operations. This part of work deals with establishing a framework for global response assessment and provides the methodology for the tools within this framework. The developed tools are applied to the initial stability analysis and the dynamic analysis of the gravitational ballasting process of a full-scale floating dock.

This chapter is partly under review as:

Zhang, J., Ong, M. C., Wen X. (2024). A Numerical Model for Stability and Dynamic Analyses of a Floating Dock during Operations. *IEEE Journal of Oceanic Engineering.* (Under review)

The PhD candidate is the first author of the paper, contributed to the work conceptualization, conducted literature study, performed numerical simulations, post-processed the results, and wrote the main manuscript. The co-authors, Prof. Muk Chen Ong, and Dr. Xueliang Wen, contributed to the work conceptualization, provided comments on the manuscript draft, supervision, and discussion of the results.

Chapter 3: The third chapter presents the verification and validation of the global response assessment tools developed in Chapter 2. The developed hydrostatic force model, 6-DOF model, and mooring force model are verified against theoretical models and various commercial software. These numerical tools are validated through experimental tests on a model-scale floating dock.

This chapter is partly under review and published as:

Zhang, J., Ong, M. C., Wen X. (2024). A Numerical Model for Stability and Dynamic Analyses of a Floating Dock during Operations. *IEEE Journal of Oceanic Engineering.* (Under review)

Zhang, J., Wen X., Kniat, A., Ong, M. C. (2024). A comparative analysis of numerically simulated and experimentally measured static responses of a floating dock. *Ships and Offshore Structures*, 1-18.

The PhD candidate is the first author of the paper, contributed to the work conceptualization, performed literature study, conducted experimental tests, performed numerical simulations, post-processed the results, and wrote the main manuscript. The co-author, Dr. Xueliang Wen, contributed to the work conceptualization, conducted experimental tests, provided comments on the manuscript draft, supervision, and discussion of the results. The co-authors, Dr. Aleksander Kniat, contributed to conducting experimental tests, provided comments on the manuscript draft and discussion of the results. and Prof. Muk Chen Ong

Chapter 4: The fourth chapter presents the automatic ballast control algorithm for floating dock operations and performs the dynamic analysis of normal de-ballasting operations.

This chapter is partly published as:

Wen X., Zhang, J., García Conde A., Ong, M. C. (2023). Numerical study on the automatic ballast control of a floating dock. *Journal of Offshore Mechanics and Arctic Engineering*, 146(4), 041401.

The PhD candidate is the second author and corresponding author of the paper, contributed to the work conceptualization, provided comments on the manuscript draft and discussion of the results. The first author, Dr. Xueliang Wen, contributed to the work conceptualization, performed numerical simulations, post-processed the results, and wrote the main manuscript. The co-author, Alejandro García Conde, performed literature study, provided comments on the manuscript draft and discussion of the results. The co-author, Prof. Muk Chen Ong, contributed to the work conceptualization, provided comments on the manuscript draft, supervision, and discussion of the results.

Chapter 5: The fifth chapter presents the dynamic analysis of de-ballasting operations of the floating dock with a malfunctioning pump, considering automatic ballast control.

This chapter is partly published as:

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The PhD candidate is the first author of the paper, contributed to the work conceptualization, conducted literature study, performed numerical simulations, post-processed the results, and wrote the main manuscript. The co-authors, Prof. Muk Chen Ong, and Dr. Xueliang Wen, contributed to the work conceptualization, provided comments on the manuscript draft, supervision, and discussion of the results.

Chapter 6: The sixth chapter focuses on modelling the dock-vessel coupling loads between the floating dock and the docked vessel and the deformation of the floating dock. Global dynamic and structural response analyses for vessel-docking operations are performed.

This chapter is partly under review as:

Zhang, J., Ong, M. C., Wen X. (2024). Dynamic and structural analyses of floating dock operations considering dock-vessel coupling loads. *Ocean Engineering*. (Under review)

The PhD candidate is the first author of the paper, contributed to the work conceptualization, conducted literature study, performed numerical simulations, post-processed the results, and wrote the main manuscript. The co-authors, Prof. Muk Chen Ong, and Dr. Xueliang Wen, contributed to the work conceptualization, provided comments on the manuscript draft, supervision, and discussion of the results.

Chapter 7: The conclusions and some suggestions on future work are given in the last chapter.