HYDRODYNAMIC INTERACTIONS AND RELATIVE MOTIONS OF FLOATING BODIES IN WAVES

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Dedicated to my beloved family

for their toleration and sincere help during my life.

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ABSTRACT

Floating structures play an important role in sea transportation as well as exploration, drilling and production of oil and gas around the world. Hydrodynamic interaction of two platforms floating close to each other affects their motion responses which hinder the loading, unloading and production operation of the floating structures. The hydrodynamic interaction between two floating bodies may lead to large amplitude motions due to low damping in low frequency. This behavior induces enormous loading in mooring system and thus possibility of the mooring system failure increases. In this research, 3D source distribution panel technique was used to find a numerical solution in frequency domain based on the potential flow theory. It was developed to compute the motions of offshore structure. For computations of the motions and relative motions of two floating offshore structures, HydroStar (Hydrodynamic analysis software developed by Bureau Veritas) was also used. In order to validate the results, model tests were carried out at the Towing Tank, Universiti Teknologi Malaysia for a semisubmersible in the vicinity of a Tension Leg Platform. The tests were conducted in a head sea condition at regular wave. Due to the limitation of water depth in the towing tank, vertical forces of the moorings were ignored and horizontal forces were modeled by horizontal mechanical spring connectors. The results obtained from the developed code, HydroStar and experimental results for a semisubmersible show a very good agreement which proves the efficiency and effectiveness of the 3D source distribution technique. Computations were also carried out for two bodies at different separation distances, wave headings and wave frequencies by using HydroStar. The results show an increase in the relative motion owing to the sheltering effect. It implies that decreasing the distance would increase the probability of accidents. From extensive numerical computations, experiments, it is concluded that a minimum gap must be maintained in order to perform safe operation. An empirical formula is also proposed from the current research for finding the minimum gap between the two structures.

ABSTRAK

Struktur terapung adalah penting dalam bidang pengangkutan di laut, bidang penjelajahan, pengerudian dan pengeluaran minyak dan gas di seluruh dunia. Interaksi hidrodinamik dua pelantar terapung berdekatan mempengaruhi respon pergerakan struktur ini, dan akan mengganggu proses muat naik dan muat turun bebanan serta operasi penghasilan struktur terapung tersebut. Interaksi hidrodinamik di antara dua benda terapung mungkin menyebabkan pergerakan amplitud yang besar akibat peredaman rendah dalam frekuensi rendah. Ini mendorong kepada bebanan yang besar pada sistem tambatan, seterusnya meningkatkan kemungkinan kegagalan sistem tambatan. Teknik panel agihan 3D digunakan untuk mencari penyelesaian berangka (numerikal) dalam domain frekuensi berdasarkan teori potensi aliran, serta untuk pengiraan pergerakan struktur luar pesisir pantai. Untuk pengiraan pergerakan dan pergerakan relatif dua struktur terapung luar pesisir pantai, Hydrostar (perisian untuk analisis Hydrodynamic yang dibangunkan oleh Bureau Veritas) juga telah digunakan. Untuk pengesahan hasil kajian, ujian model telah dijalankan di Tangki Tunda (Towing Tank) di Universiti Teknologi Malaysia bagi struktur separa tenggelam dalam sekitar *Tension Leg Platform*. Ujian dijalankan pada arahtuju laut pada keadaan ombak sekata. Disebabkan batasan kedalaman air dalam tangki tunda, tenaga menegak daripada tambatan tidak diambilkira, dan tenaga melintang dimodelkan dengan penyambung spring mekanikal melintang. Hasil kod Hydrostar dan hasil eksperimen untuk struktur separa tenggelam menunjukkan kesamaan; mengesahkan keberkesanan teknik agihan sumber 3D. Pengiraan juga telah dilakukan untuk dua struktur pada jarak pemisahan berlainan, arahtuju ombak dan frekuensi ombak menggunakan Hydrostar. Hasil kajian menunjukkan peningkatan dalam pergerakan relatif akibat kesan teduhan, dan pengurangan jarak akan meningkatkan kemungkinan pelanggaran. Kesimpulan dari kajian yang mendalam menunjukkan jarak minimum perlu dikekalkan untuk perlaksanaan operasi dengan selamat. Kajian ini juga menyarankan satu formula empirikal untuk mencari jarak minimum di antara dua struktur.

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LIST OF ABBREVIATIONS

BEM	-	Boundary Element Method
BUET	-	Bangladesh University and Engineering Technology
CFD	-	Computational Fluid Dynamics
DAAS	-	Data Acquisition System and Analysis System
DAQ	-	Dewetron Data Acquisition System
DES	-	Drilling Equipment Set
DNV	-	Det Norske Veritas
DP	-	Dynamic Positioning
FLNG	-	Floating Liquefied Natural Gas
FOWT	-	Floating Offshore Wind Turbine
FPSO	-	Floating Production Storage and Offloading
GM	-	Metacentric Height
KG	-	Vertical Center Of Gravity
LNG	-	Liquid Natural Gas
MTC	-	Marine Technology Center
PMM	-	Planar Motion Mechanism
RANS	-	Reynolds Averaged Navier Stokes
RAO	-	Response Amplitude Of Operation
SCR	-	Steel Catenary Risers
TAD	-	Tender Assist Drilling
TiMIT	-	Time-domain, free-surface, radiation/diffraction first order code developed at Massachusetts Institute of Technology
TLP	-	Tension Leg Platform

TPS	-	Truss pontoon semisubmersible
TTR	-	Top Tension Riser
UTM	-	Universiti Teknologi Malaysia
WAMIT	-	Wave Analysis frequency-domain, free-surface, radiation /diffraction code developed at Massachusetts Institute of Technology

LIST OF SYMBOLS

a_{kj}^{m}	-	Added mass coefficient matrix of *kj*
a0 or ζa	-	Surface incident wave amplitude
a_{kj}	-	Added mass coefficient matrix of *kj*
b_{kj}^{m}	-	Damping coefficient matrix of *kj*
[B]	-	Damping matrix
b_{kj}	-	Damping coefficient matrix of *kj*
C	-	Hydrostatic restoring force coefficient matrix of *kj*
CF_X	-	Center of Floatation from the x axis
CF_Y	-	Center of Floatation from the y axis
CG_X	-	Center of Gravity in x direction
CG_Y	-	Center of Gravity in y direction
CG_Z	-	Center of Gravity in z direction
F	-	Vector of the incident wave force
F_{k}^{m}	-	k^{th} component of wave exciting forces or moments on the body m
F_{kj}^{m}	-	k^{th} component of force arising from the j^{th} component of motion of the body m
F_k	-	k^{th} component of wave exciting forces
F_{kj}	-	k^{th} component of force arising from the j^{th} component of motion of the body
F_n	-	Froude number
g	-	Gravitational acceleration
G_{aa}, G_{ba}, G_{bb}, G_{ab}	-	Green functions with respect to ϕ_{7aa}, ϕ_{7ba}, ϕ_{7bb} and ϕ_{7ab}
GM_L	-	Longitudinal Metacentric height

GM_T	-	Transverse Metacentric height
h	-	Depth of the water
H	-	Wave height
H(1/20)	-	Wave slope (wave amplitude to wave length)
J_0	-	Bessel functions of the first kind of order zero
k	-	wave number (ω2/g)= 2π/L
[K]	-	Stiffness matrix
k_1, k_2	-	The wave number components in x and y directions.
K_C	-	Linearized connecting stiffness matrix of *kj*
KC	-	Keulegan–Carpenter number
K_0	-	Modified Bessel function of the second kind of order zero.
K_m	-	Linearized mooring line stiffness matrix of *kj*
k	-	Linearized connector stiffness
K_{XX}	-	Gyration radius about x axis
K_{YY}	-	Gyration radius about y axis
K_{ZZ}	-	Gyration radius about z axis
l_{BB}	-	Length between centers of buoyancies of two platforms.
LCB	-	Longitudinal center of buoyancy
l_{GO}	-	Original gap length between two platforms
l_{min}	-	Minimum safe gap distance
l_T	-	Total length of two platform plus original gap between them
M_{kj}^{m}	-	Inertia matrix in k mode due to the motion in *j* mode
[M]	-	Inertia matrix of the body
[Ma]	-	Additional mass matrix
M_{kj}	-	Inertia matrix in k mode due to the motion in *j* mode
$\vec{n}$	-	Unit normal vector to the surface
p	-	Field point

q	-	Source point
Re	-	Indicates the real part of the complex value between brackets.
T	-	Period
Tn	-	Natural period
U	-	Motion vector of the body
$\vec{V}$	-	Velocity vector
x_G^m, y_G^m, z_G^m	-	Coordinate of the centre of gravity of the body m
X_{ja} , X_{jb}	-	Response motion of mode *j* of structure *a* or structure *b*
X_j^m	-	Vectors containing the three translational and three rotational oscillations about the coordinate axes in *j* mode
X_j^m	-	motion amplitude of the body m in j^{th} mode
x, y, z	-	Investigating point on the wetted surface of the body
X_1, Y_1, Z_1	-	Coordinate of connector at sea
X_2, Y_2, Z_2	-	Coordinate of connector at fairlead
x_m, y_m, z_m	-	Investigating point on the wetted surface of the body *m*
x_G, y_G, z_G	-	Coordinate of the center of gravity of the body
X_j	-	A vector containing the three translational and three rotational oscillations about the coordinate axes in *j* mode
Y_0	-	Bessel functions of the second kind of order zero
α or μ	-	Wave heading angle from *X* axis
$\Re$	-	Pontoons volume to semisubmersible displacement ratio
(ξ, η, ζ)	-	Point on surface *S*
σ(ξ, η, ζ)	-	Unknown source distribution
σ_a , σ_b	-	Source intensity of wetted structure surface *a* and *b*
σ_{a1}, σ_{b1}, σ_{a2} , σ_{b2}	-	Source intensity on the wetted surface *a* and *b* due to j^{th} mode motion of structures *a* and *b*
ϕ	-	Complex time independent quantity.
ϕ_0	-	Incident wave potential and for long crested harmonic progressive waves
ϕ_7	-	Diffraction waves potential on the body

ϕ_j	-	Potential due to motion of the body in j^{th} mode
ϕ_j^m	-	Potential due to motion of body *m* in j^{th} mode i.e. radiation wave potentials
ϕ_{0a}, ϕ_{0b}	-	Potential of incident waves on structure *a* and structure *b*
ϕ_{7aa}, ϕ_{7ba}	-	Diffraction potential on structure *a* due to structure *a* or structure *b*
ϕ_{7bb}, ϕ_{7ab}	-	Diffraction potential on structure *b* due to structure *b* or structure *a*
ϕ_{jRaa}, ϕ_{jRab}	-	Radiation potential on structure *a* or structure *b* due to oscillation of structure *a* while structure *b* is fixed
ϕ_{jRba} , ϕ_{jRbb}	-	Radiation potential on structure *a* or structure *b* due to oscillation of structure *b* while structure *a* is fixed
λ	-	Wave length
ω	-	Circular frequency of incident wave *(2π/T)*

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CHAPTER 1

INTRODCTION

1.1 Background

Tender Assist Drilling (TADs) units were the rig of choice in the 1950s and early 1960s in the Gulf of Mexico for development drilling off fixed platforms. Although they are used less commonly now, they are appropriate for certain situations such as new drilling from an aging platform near shore. The monohull tenders tended to lose location with mooring failures during storms. This occurrence, along with severe motions of the tender, resulted in their losing favor, except for use in very mild or benign environments, such as in the Far East and West Africa. The TAD advantage is that its DES (Drilling Equipment Set) is relatively lightweight, one-quarter to one-fifth the weight and one-third the space of a standard platform rig. Most TADs carry the DES on the tender hull and are self-erecting, so no workboat or derrick barge is required. They are particularly attractive for situations in which there is an old platform with reduced load-carry ability and/or space, such as when a platform is drilled with a standard platform rig, and then production equipment is loaded onto the platform, eliminating space and load-carry capacity (PetroWiki, 2014). In this research, TLP as a well head platform works with a semisubmersible for Tender Assist Drilling (TAD) operation.

It is not unusual for a platform to deteriorate with age, and then be unable to hold up a standard platform rig when additional wells need to be drilled. The TAD is an option for this situation. For spars and TLPs in deep water where weight and space are at an absolute premium, TADs, particularly semi TADs with their lightweight DES, have significant advantages in some cases over a modular platform rig. Semi TADs also have the advantage of acting as construction barges for platforms that are commissioning production equipment. They offer a relatively inexpensive construction platform compared with a construction derrick barge due to the large rig-up crane, open decks where the DES is stored and transported, accommodations, general facilities and amenities.

The reliable prediction of the seakeeping behavior of platforms in real seas is a demanding task for naval architects and ocean engineers. It is also of great practical interest to ship owners and users, as it affects both the design and operation of ships and Platforms. There are different theories for studying motion of floating structures such as strip theory and potential flow theory. In this research work, a 3D source density distribution technique was used to get the potential flow amounts over the floating structure. The method utilizes a source density distribution on the surface of the body and solves the distribution necessary to make the normal component of the fluid velocity zero on the boundary. The underwater part of the floating structure is divided into a number of panels.

Plane quadrilateral surface elements are used to approximate the body surface, and the integral equation for the source density is replaced by a set of linear algebraic equations for the values of the source density on the quadrilateral elements. When this set of equations has been solved, the flow velocity both on and off the body surface is calculated. In this way, incident wave potential, scattered wave potential and radiation wave potential are calculated at each panel. All related velocity potentials applied in the calculations are in 3D form.

By having the flow velocity potentials on and off the panels, we can predict the hydrodynamic coefficients of floating structure. Using Bernoulli's equation leads to calculation of pressure distribution and forces over the floating structure and gets amount of motion. One of the most concerned problems on the development of floating structures is an undesirable large motion response between two or more floating structures.

In general, many offshore operations involve the use of two or more floating structures which are positioned close to transfer oil or gas during offloading so that they affect each other's motion response through hydrodynamic interaction in waves. Consequently, the large motions between two floating bodies may cause them to collide with each other and hence damage the operation systems,. Because of these serious problems during operation, it is very important to study the motion behaviors between two floating bodies due to the hydrodynamic interaction effect.

Floating structures such as ships, semisubmersibles, Floating Production Storage and Offloading (FPSO), Tension Leg Platforms (TLP), Tender Assist Drilling (TADs) units, breakwater and other free floating or moored structures, are subject to waves, winds and currents at sea. They have six-coupled degrees of freedom of motions. Namely, translational motions are the surge, sway and heave, and angular motions are the roll, pitch and yaw (Figure 1.1). Oscillation of the floating structures affects the operation systems.

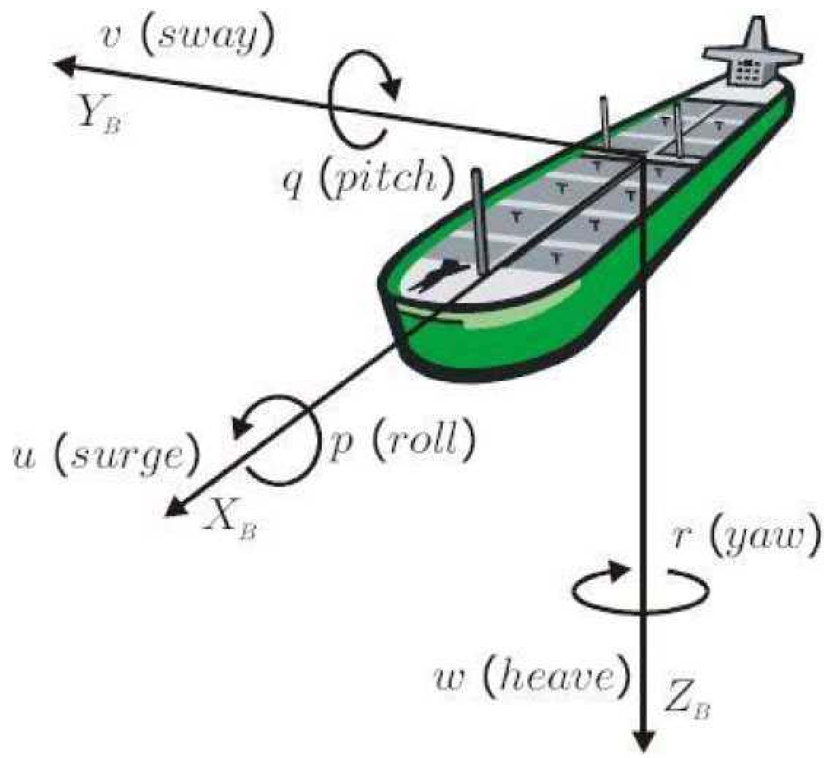

Figure 1.1 Motions of a floating body in six degrees of freedom

1.2 Problem statement

Nowadays, Computational Fluid Dynamics (CFD) products based on solving Reynolds-Averaged-Navier-Stokes (RANS) equations have demonstrated their capabilities in almost every aspect of ship/platform hydrodynamic problems, nevertheless they are still very time-consuming and even with the utilization of the most advanced computational power they are still not able to conduct seakeeping assessments with proper accuracy and within desirable time. Thus the development of alternative methods based on potential flow theory is still attractive and necessary as they are much more efficient to implement. According to the study in literature review, most researchers have mainly focused on the interaction and relative motion of ship shaped structures while they have very rarely paid attention to the platforms.

1.3 Objectives of the study

The objectives of this research are as follows:

- To investigate the hydrodynamic forces of one and two floating platforms in regular waves.
- To identify motion and relative motion of single and two floating platforms in waves.
- To develop a computational tool for calculating hydrodynamic forces and motions.
- To conduct experiment for validating the numerical calculation results.

1.4 Scope of the study

The aim of the present project is to study the hydrodynamic characteristics of single and double floating platforms. This investigation has been carried out by numerical and experimental methods, each consisting of several steps. The scopes of this research work are as follows:

- The literature review was carried out on hydrodynamic characteristics of the usual type of oil and gas offshore platforms. This literature revealed the current work of researchers on platform types and their hydrodynamic behaviors in deep water. This step made a useful guideline for the present research work.
- The potential flow technique was used for the numerical analysis of the hydrodynamic characteristics of the floating structures. Three steps, preprocessing, solving, and post processing were discovered in potential flow theory method.

    - Preprocessing included designation of the platform model and the computational domain, mesh generation, definition of fluid properties, selecting the governing equations, and the definition of boundary condition of domain boundary.
    - Discretization of the integral equations to find algebraic equations.
    - The solution of the algebraic equations by an iterative method has been determined.
    - Discussions and analysis have been performed with plots and contours of the results in the post processing stage.

- Numerical simulations were carried out at different wave directions and wave frequencies.
- The hydrodynamic forces of single and double bodies have been measured by experiments in the wave heading at different wave frequencies and different wave heights in the towing tank of Universiti Teknologi Malaysia. The hydrodynamic forces and motions were measured with a six component dynamometer system and Qualisys camera.
- The tests models were built from wood at the Marine Technology Center.

- Computations of hydrodynamics forces and motions were made by HydroStar, commercial well-known software.
- The results were evaluated by experimental works.

1.5 Significance of the study

Since the demand for oil and gas is growing, deeper and deeper waters are to be explored, and the chance of multi-body operation at close proximity is increasing, so investigating the reliability of a numerical analysis method for hydrodynamic interaction is worthwhile. The present research focuses both numerically and experimentally on the hydrodynamic interaction between two offshore platforms in regular waves. While conducting the test is very expensive, numerical study is not and still acceptable. In this research a systematic procedure is followed to study the dynamics of floating structures under incident, radiation, and scattered waves and to find their hydrodynamic interactions and relative motions. Besides developing a computer code for single body, two floating structures were simulated in offshore engineering software in different separation distances, in different wave slopes and in different incident wave frequencies. Finally, model test was carried out to validate the numerical results. The tests were done individually and two bodies in the vicinity of each other. The results of this project can be used for design of floating offshore platforms.

1.6 Organization of the thesis

This thesis is organized in nine chapters. The present chapter provides an overview of the present research work. Based on the literature review, the objectives and scope of the present study are also explained in this chapter. Additionally, the significance of this investigation is provided.

Chapter two presents a detailed review of the earlier research work related to the present investigation. For the clarity of presentation, the literature review has been grouped under different headings namely, oil and gas structures including semisubmersibles, TLPs and spars, Pontoons and columns size effects, classification of structures based on hydrodynamic behavior, double bodies and sheltering effects, motion and relative motion.

In chapter three numerical and experimental research methods are presented. It describes the mathematical model, its assumptions and limitations, numerical simulation, and analyzing in the frequency domain. The experimental methodology firstly gives a background about towing tank and introduces the low speed towing tank of Universiti Teknologi Malaysia. Next, some description is given about the facilities, preliminary tests, set-up of experiment and procedure of test.

Chapter four presents the basic concepts, techniques and numerical procedures used for the evaluation of hydrodynamic forces and motions for the multi-body systems subject to wave motion. The mathematical model in this chapter is derived based on Newton's second law. The numerical procedure for calculating first order forces and motions based on the three-dimensional source distribution technique are described in detail.

Chapter five explains the numerical code which is developed in FOTRAN based on Boundary Element Method (BEM).

Chapter six shows the numerical results for the first order motions responses of a single moored semisubmersible in a head sea using a home program. It shows model particulars, explains on decay test, and calculates natural periods of the floating body. The motion of the semisubmersible is also obtained by using the well-known commercial offshore-engineering software HydroStar (Chen, 2010) and model tests. The comparison of the results shows a very good agreement.

The hydrodynamic interaction and relative motion of the semisubmersible and a TLP are experimentally measured in chapter seven. There are some comparisons between the semisubmersible and the TLP motions in surge, heave and pitch direction at different encounter frequencies.

In chapter eight the simulation of the two platforms is carried out at vicinity of each other. The procedure of simulation in the HydroStar is explained briefly. The motions and relative motions of two floating bodies are studied individually and together at different separation distances and incident wave heads. The obtained results are compared with the model test results and achieve a very good agreement. In some frequencies the model test is carried out at different wave slope and found that the more slope wave has higher responses.

Chapter nine presents the summary and discussion on the basis of the present investigation which can be a valuable tool for the future design of a multi-body system or for huge floating structures as a drilling and exploration, a floating airport or bases.

Finally, chapter ten presents the major conclusions drawn from the numerical simulation and model test experiments on single and double bodies. In addition, recommendations for future studies in this field have also been presented in this chapter.

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