SEAKEEPING EVALUATION OF SEMI-SWATH VESSEL IN HEAD-SEAS USING TIME DOMAIN SIMULATION

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ABSTRACT

Small Waterplane Area Twin Hull (SWATH) and Catamaran vessels are known to have more stable platform as compared to mono-hulls. A further advantage of SWATH as compared to Catamaran is its smaller waterplane area that provides better seakeeping qualities. However, the significant drawback of the SWATH vessel is when encountering head-sea at high forward speed. Due to its low stiffness, it has a tendency for large pitch motions. Consequently, this may lead to excessive trim or even deck wetness. This phenomenon will not only degrade the comfortability but also results in structural damage with greater safety risks. In this research a modified SWATH design is proposed. The proposed design concept represents a combination of Catamaran and SWATH hull features that will lead to reduce in bow diving but still maintains good seakeeping capabilities. This is then called the **Semi-SWATH vessel.** In addition, the full-design of this vessel has been equipped by fixed fore fins and controllable aft fins attached on each lower hull. In the development of controllable aft fins, the PID controller system was applied to obtain an optimal vessel's ride performance at speeds of 15 (medium) and 20 (high) knots. In this research work, the seakeeping performance of Semi-SWATH vessel was evaluated using time-domain simulation approach. The effect of fin stabilizer on the bare hull performance is considered. The validity of numerical evaluation was then compared with model experiments carried out in the Towing Tank at Marine Technology Laboratory, UTM. It was shown that the Semi-SWATH vessel with controllable fin stabilizer can have significantly reduction by about 42.57% of heave motion and 48.80% of pitch motion.

ABSTRAK

Kapal dwi-hull satah air kecil (SWATH) dan katamaran mempunyai pelantar yang lebih stabil berbanding kapal biasa. Keluasan satah air SWATH yang lebih kecil berbanding katamaran menyebabkan SWATH mempunyai kelebihan dalam keupayaan tahan laut. Walaupun demikian, SWATH menghadapi masalah apabila bertembung dengan ombak dari arah depan pada kelajuan tinggi. Dengan mempunyai sifat kekakuan yang rendah, SWATH berkecenderungan untuk mempunyai pergerakan anggul yang besar. Ini akan memberi kesan trim yang melampau dan juga boleh menyebabkan air melimpah ke dalam geladak kapal. Fenomena ini bukan sahaja akan menyebabkan SWATH menjadi tidak selesa untuk penumpangnya malah struktur kapal juga mungkin akan rosak dan seterusnya kapal menjadi tidak selamat. Kajian ini mencadangkan SWATH yang diubahsuai berkonsepkan penggabungan struktur badan kapal SWATH dan katamaran yang akan mengurangkan kesan junaman haluan tetapi masih mengekalkan keupayaan tahan laut yang baik. Ia dinamakan sebagai **Semi-SWATH**. Sebagai tambahan, rekabentuk keseluruhan kapal ini dilengkapi dengan sirip tetap di bahagian haluan dan sirip boleh kawal pada setiap bahagian belakang lunas kapal. Sistem kawalan PID digunakan untuk merekabentuk sirip buritan boleh kawal bagi memastikan pencapaian kapal pada kadar optima pada kelajuan 15 (sederhana) dan 20 (tinggi) knots. Di dalam kajian ini, pencapaian ketahanan laut bagi Semi-SWATH diperolehi dengan pendekatan simulasi masa dengan mengambil kira kesan penstabilan sirip yang diletakkan pada badan kapal. Penilaian menggunakan kaedah berangka tersebut kemudiannya dibandingkan dengan hasil eksperimen pengujian model yang dijalankan di Makmal Teknologi Marin, UTM. Didapati Semi-SWATH dengan sirip boleh kawal memberikan pengurangan lambungan sebanyak 42.57% dan 48.8% pengurangan anggul.

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NOMENCLATURE

Vessel/ Environment Parameters

Δ_d	:	Displacement at deep draught
Δ_s	:	Displacement at shallow draught
Cb	:	Block coefficient
C_m	:	Midship area coefficient
GM_L	:	Longitudinal metacentric height
GM_T	:	Transverse metacentric height
KG	:	Vertical height of centre of gravity from the Keel
LCG	:	Longitudinal center of gravity
LOA	:	Length overall of ship
SWATH	:	Small Waterplane Area of Twin Hull
T_d	:	Deep draught
T_s	:	Shallow draught

PID Controller

δ_c	:	Control variable
a	:	The amplitude of the waveform oscillation
Controller	:	Provides the excitation for the plant; Designed to control the overall system behaviour
d	:	Amplitude of the relay output
e	:	The error deviations
K_c	:	Critical gain
K_d	:	Derivative gain

K_i, : Integral gain

K_p, : Proportional gain

MIMO : multiple-input multiple-output

PID : Proportional-Integral-Derivative

Plant : A system to be controlled

POS : Percent overshoot

SISO : Single-input single-output

T_c : Critical period of waveform oscillation

T_d : Derivative time constant

T_i : Integral time constant

Y_{ref} : A desired response

DC Motor

θ : Angular displacement [rad]

ω : Motor shaft angular velocity [rad/sec]

i_a : Motor Current [A]

Jm : Motor Inertia [$Nm.sec^2$]

K_a : Back emf constant [mV/(rad/sec)]

K_m : Torque Constant [Nm/A]

L_a : Motor Inductance [H]

R_a : Motor Resistance [Ω]

T_L : Load Torque [Nm]

T_m : Motor Torque [Nm]

V_a : Motor Voltage [V]

Co-ordinate Systems

$O^e x^e y^e z^e$: The earth fixed co-ordinate system

$O^* x^* y^* z^*$: The fixed ship system being located at the centre of gravity of the ship

Fin Stabilizer

ρ	:	Fluid density
A_{ij}^{f}	:	Added mass of fin
B	:	Body
X_{FP}	:	Distance from the ship forward perpendicular to the fin axis
C_D	:	Drag coefficient
E_{FS}	:	Effect of free surface
$C_{L\alpha}$	:	Lift coefficient of the fin
$C_{Z\alpha}$	:	Lift coefficient of the fin attached to the hull
M_{ij}^{f}	:	Mass of fin
D	:	Maximum diameter of the hull
ω	:	Oscillation frequency
A	:	Projected fin area
R_n	:	Reynolds number
t	:	The maximum thickness of the fin
a	:	Hull radius
K and k	:	Fin-hull interaction factors for a fixed fin and for an activating fin
AR	:	Aspect ratio
c	:	Chord
D	:	Distance between leading edge of fins
KC	:	Keulegan Carpenter
s	:	Span
T	:	Encounter period
W	:	Wing

Equations of Motion

F_x, F_y, F_z	:	Force acting in x, y and z direction respectively
I_x, I_y, I_z	:	Principal mass moments of inertia about the x, y and z axes respectively

m	:	Mass of body
p, q, r	:	Angular velocities along the respective x, y and z axes
u, v, w	:	Linear velocities along the respective x, y and z axes

Forces and Moments

$\vec{U}$	:	Forward speed
$\bar{q}$	:	Complex conjugate of q
u_a	:	Motion amplitude
$\frac{\partial}{\partial n_q}$	:	Normal derivative with respect to the source point q
$\vec{n}$	:	Outward unit normal vector
q	:	Source point
G	:	Two dimensional Green's function
∇	:	Vector differential operator
ξ_a	:	Wave amplitude
ρ	:	Density of water
ω	:	Frequency of excitation
ν	:	Real variable
ϕ	:	Time dependent velocity potential
∇	:	Under water volume of vessel
ϕ_D	:	Diffracted wave potential
ω_e	:	Frequency of encounter
ϕ_I	:	Incident wave potential
ϕ_{Rj}	:	Generated wave potential due to motions of the body in the j^{th} direction
ϕ^R and ϕ^I	:	Velocity potentials
g	:	Gravitational acceleration
n_j	:	Outward unit normal vector in the j^{th} mode of motion
p	:	Field point

p	:	Pressure acting on the wetted surface
PV	:	Denotes Principal Value of an integral
S_b	:	Wetted body surface
S_f	:	Free surface

Hydrodynamic Coefficients

a_{jj}	:	Hydrodynamic reaction in phase with acceleration (added mass) in the j^{th} direction (j = 1,2,…,6)
b_{jj}	:	Hydrodynamic reaction in phase with velocity (damping) in the j^{th} direction (j = 1,2,…,6)
c_{jj}	:	Hydrostatic stiffness of body in the j^{th} direction (j = 1,2,…,6)
m_j	:	Mass or mass moment of inertia of body in the j^{th} direction (j = 1,2,…,6)

Experiment

ω_n	:	Natural frequency of ship
λ	:	Wavelength
DAAS	:	Data Acquisition and Analyzing System
Ls	:	Length of ship
RAO	:	Response Amplitude Operators
SCS	:	Signal Conditioning System

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CHAPTER 1

INTRODUCTION

1.1 Background

The applications of twin-hull vessels particularly SWATH vessel and conventional Catamaran have widely designed regarding for purpose of providing better seakeeping quality than mono-hull vessels inherently.

Holloway and Davis (2003) and Kennell (1992) stated that inherent to the advantages of SWATH vessels, as compared to the conventional Catamaran is its smaller waterplane area that provided smaller wave excitation forces, lower amplitude motion associated with its lower accelerations responses and better seakeeping performances. Dubrovskiy and Lyakhoviyskiy (2001), Fang (1988) and Kennell (1992) mentioned that due to its smaller waterplane area, the SWATH vessels have larger natural period as twice as long the natural periods of roll, pitch, and heave of a mono-hull of comparable size.

Based on Dubrovskiy and Lyakhoviyskiy (2001) and Ozawa (1987) have presented the advantages of conventional Catamaran features compared to the SWATH vessels have shallower draft and lower cost of construction. Their larger waterplane areas as compared to the SWATH vessel has increased the stiffness as result as improve vessel's longitudinal stability.

Conversely, the particular drawbacks of SWATH vessel and conventional Catamaran geometrically cannot be neglected. It is shown that the SWATH vessel with its small waterplane area is tender in large pitch motion due to low stiffness resulted as increase in speed. Djatmiko (2004), and Dubrovskiy and Lyakhoviyskiy (2001), Katayama (2002), and Kennell (1992) stated that the low value of this parameter is linked to its insufficient values of longitudinal metacentric height (GM_L). Consequently, this may lead to pitch instabilities, which caused slamming, deck-wetness, excessive trim or even bow diving and degrade the passenger comfortability.

Having considered some extensive reviews of several obtainable advantages both SWATH and conventional Catamaran hull forms, an alternative hull form design is proposed to overcome and minimize their drawbacks. The proposed design concept represents a combination of conventional Catamaran and SWATH hull features. In addition, this new modified hull form configuration conceptually was emphasized on the variable draught operations i.e. shallow draught and deep draught. Then, this vessel is called "**Semi-SWATH vessel**."

Holloway (1998 and 2003) investigated that as the hybrid design hull form; the Semi-SWATH configurations generally offered two ways that make the most of Semi-SWATH vessel's benefits. First, its primary premise is to maintain a good seakeeping quality. Second, it is intended to prevent the bow diving phenomena at high-speed. It means the maturity of Semi-SWATH vessel is going to provide an improvement of conventional Catamaran and SWATH vessel drawbacks considerably.

Furthermore, the placement both of fixed bow fins and controllable stern fins on each lower hull of Semi-SWATH vessel will provide additional pitch restoring moment to improve not only the longitudinal stability but also reduce the vertical motion responses. Consequently, the serious inconveniences will degrade the vessel performance during sailing especially at high-speed head sea waves can be alleviated. Haywood, Duncan, Klaka, and Bennett (1995) stated that the seakeeping of the Semi-SWATH vessel is going to be better evidently.

The simulation program of Semi-SWATH vessel incorporated with fixed fore and controllable aft fins were developed to evaluate the seakeeping performance during operation at both medium speed (15 knots) and high-speed (20 knots). The mathematical model comprising of heave and pitch motions, which incorporated with the fins stabilizers on the simulation was presented in a simple block diagram using Matlab-SIMULINK. In this simulation, a conventional PID controller was developed and applied on the controllable aft fins. Segundo, et al (2000) developed simulation program using PID controller to alleviate vertical accelerations due to waves. The results of simulation had been validated by experiments in the towing tank confirm that by means of flaps and a T-foil, moved under control, vertical accelerations can be smoothed, with a significant improvement of passengers comfort. In addition, Caldeira, et al (1984), Ware, et al (1980a), (1980b), 1981, and 1987, and Chinn, et al (1994) applied conventional optimal PID controller design to improve the vertical motion response of marine vehicles.

In this PID controller method, some parameter of tuning controller will involve some chosen controller gain parameters of PID (K_p, K_i, *and* K_d are the proportional, integral, and derivative gains, respectively). Those parameters are obtained using method of Aström and Hagglund. Then, they will be considered to satisfy certain control specifications by minimizing the error after achieving steady state. This controller mode is applied by controlling the aft fin's angle of attack properly, the sailing style of Semi-SWATH vessel must be adjusted to be in even keel condition. The theoretical prediction results will be validated with the model experiments carried out in the Towing Tank of Marine Technology Laboratory, Universiti Teknologi Malaysia.

1.2 Research Objective

1. To evaluate the seakeeping performance of Semi-SWATH vessel before and after installation both of fixed fore and controllable aft fins in regular head sea using time domain simulation and validated by model test in Towing Tank.

2. To apply a ride control system on the controllable aft fins, the conventional PID controller will be used to achieve a better quality the Semi-SWATH seakeeping performance.

1.3 Scopes of Research

1. The mathematical dynamics equations model covers Semi-SWATH vessels with fins in two degrees of freedoms i.e. heave and pitch motions operating in regular head sea.
2. The numerical method simulation is based on Time-Domain using Matlab-SIMULINK.
3. In the simulation, the regular waves generated using MATLAB for any wavelength of interest as well as experiment done (range of regular wave lengths: $0.5 \leq \lambda/L \leq 2.5$ and steepness of the incident wave: $H/\lambda = 1/25$)
4. The hydrodynamic coefficients of Semi-SWATH vessel motions will be obtained using numerical program, which was developed by Adi Maimun and Voon Buang Ain (2001).
5. The proper fin stabilizers were selected using NACA-0015 section due to high lift curve slope and low drag.
6. Lift Coefficient (C_L) will be obtained using CFD software (Shipflow 2.8).
7. A conventional PID controller will be applied on the Semi-SWATH vessel to improve the stability and performance of plant system with adequate reliability.
8. A parameter tuning of PID controller is obtained using method of Aström and Hagglund i.e. K_p, K_i, *and* K_d. Then, they will be applied to satisfy certain control specifications by minimizing the error after achieving steady state.
9. The simulation program result will be validated of by the Semi-SWATH model test carried out in Towing Tank of Marine Technology Laboratory, Universiti Teknologi Malaysia.

1.4 Research Outline

An achievement of the excellent seakeeping qualities for ship design requires extensive consideration as guidelines to reflect the safety, effectiveness, and comfort of vessel in waves. The present research follows a systematic procedure to modify concept design of twin-hull vessel by minimizing their drawbacks. This study starts from the review of SWATH and conventional Catamaran hull forms. The final design of the new modified hull form will deal to enhance the vessel's stiffness associated with improving seakeeping qualities at high-speed in head seas waves condition. Then this vessel is called Semi-SWATH vessel.

The flexibility of the Semi-SWATH vessel can be operated in two variable draughts i.e. shallow draught and deep draught with still maintain seakeeping quality. In these variations of operational draughts, the Semi-SWATH vessel will be operated in two speed services i.e. medium speed (15 knots) and high-speed (20 knots). Furthermore, the effects of vertical motions on the Semi-SWATH vessel (heave and pitch motions) when encountering head sea at those service speed will be investigated considerably.

For this reason, an advanced prediction analysis both numerically and experimentally to achieve a desired goal will be done. In stage of the Time-Domain Simulation approach theoretically will be used to predict and analyze the seakeeping performance in head sea waves, which was developed using Matlab-SIMULINK. Then, the mathematical model comprising of heave and pitch coupled motions before and after attached fixed bow and active stern fin stabilizers are investigated. Then, the conventional PID controller is applied on the active stern fin stabilizer by tuning its angle of attack to enhance the improvement of ride quality ideally to be even keel riding condition. Then, the real-time simulation results will be validated by experimental model test carried out in Towing Tank at Department of Marine Technology, Universiti Teknologi Malaysia.

Finally, the seakeeping evaluation of Semi-SWATH vessel is identified based on the motion response, which presented by Response Amplitude Operators (RAOs).

The outline of thesis organization is shown in Figure 1.1.

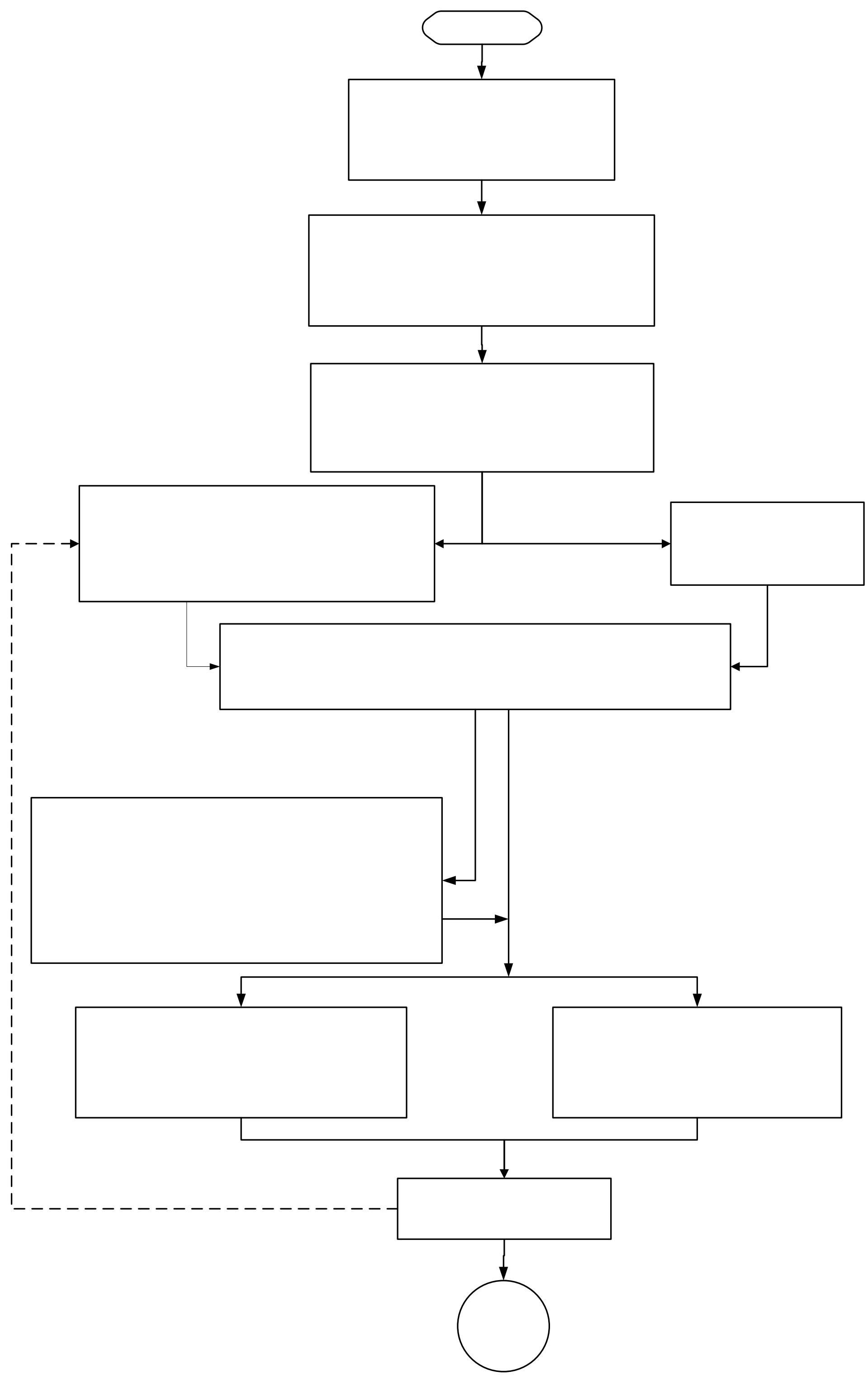

Figure 1.1 Outline of the thesis organization