

Investigating the Motions Behavior of a Ferry in Waves Caused by Damaged Conditions

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Abstract— a progressive flooding-ingress of water to a compartment of a damaged ship affects the motions of a ship. In this present study, the behavior of the motion of a ferry caused by damaged conditions in waves was investigated through the experimental work. The leakage of compartments was made into several scenarios including one, two, and three damaged compartments, and the damaged ship model was simulated in heading and beam waves. The research results show the one damaged compartment on the engine room (ER) affected extreme stern trim as well as Void No.1 affected extreme bow trim. The two damaged compartments on the water ballast tank (WBT) No.2 and Steering gear room (SGR) resulted in extreme stern trim as well as WBT No.1 and Void No.1 affected extreme bow trim. The heave, pitch, and roll responses on the damaged Void No.1 are higher comparing with the damaged ER. Also, the heave, pitch, and roll responses on damaged SGR and WTB No.2 are higher than Void No.1 and WBT No.1. The peak resonances of heave RAO on bow trim affect higher magnitude than on stern trim. Pitch or roll RAO caused by the increased bow trim or stern trim in head and beam waves has a small magnitude within the response.

Keywords—beam wave, damaged ship, heading wave, heave motion, pitch motion, response amplitude operator (RAO), roll motion.

I. INTRODUCTION¹

When a damaged ship is sailing in a wave, the ship's behavior is not only influenced by the excitation of ocean waves but is also influenced by the charge of liquid inside the ship caused by water leaks and sloshing. At the same time, the hydrodynamic characteristics of water flooding and sloshing are also affected by the motions of the ship. Those experiencing conditions will surely endanger a damaged ship at actual sea. Therefore, a ship must be designed properly by consideration not only in an intact condition but also in a damaged condition using the physical understanding of the damaged ship behavior.

Some studies have been attempted into various approaches in order to investigate the performance of the damaged ship. The mathematical modeling of motions and damaged stability of Ro-Ro ships in the intermediate stages of flooding developed [1]. Through the WEGEMT workshop on damage stability of the ships in 1995, there were several related studies of damaged ships that presented. In this workshop, the calculation of probabilistic damage stability in preliminary ship design was presented [2], the probability of damage with water ingress and the consequences of damage was identified and analyzed using probabilistic methods [3], the damage stability of Ro-Ro Ferries in rough seas was investigated by model testing [4,5].

Correspondingly, the investigation of the capsizing phenomena of a damaged ship has been done such as the capsizing of damaged Ro-Ro passenger ships in waves [6], extreme motions and capsizing of ships and offshore marine vehicles [7], the sinking of the passenger/Ro-Ro ferry caused by ship's damage stability [8]. The sloshing

was considered on the ship dynamics by the use of a simplified lump mass concept [6]. Obviously, progressive flooding through open left watertight doors was found to be the main reason for the ship's sinking [8]. Then the development of numerical motions modeling of the damaged ship was done taking into account floodwater dynamics [7, 9]. The integrated numerical method which couples a seakeeping solver and a Navier-Stokes (NS) solver with the volume of fluid (VOF) model to study the behavior of a damaged ship in waves was developed [10, 11]. The coupling motion of heave, pitch, and roll of the intact ship and damaged ships in waves was simulated based on viscous theory [12]. The motions of the damaged ship in calm water and regular beam waves were analyzed through CFD methods [13]. This must be noted that the motions of ferry ships are very vulnerable in wave due to leakage in its compartments caused by damage happened.

On the other hand, the experimental study of damaged ships is also an important way and it has been done in order to investigate a damaged ship behavior. The followings are some experimental studies that have been conducted. The behavior of a damaged Ro-Ro ship model with water on the car deck in beam waves was investigated experimentally [14]. The experimental investigation using an International Towing Tank Conference (ITTC) Ro-Ro ferry was carried out to provide a thorough insight into the flooding physics [15]. The experimental prediction of motions of frigate hull in intact and damaged conditions at zero speed showed the changes in motion responses [16]. The compartment permeability influence on damaged ship motions indicated a non-linear effect on heave and pitch motions of a damaged ship [17]. The ingress and egress of floodwater and the interaction between ship behavior and water surface effect have a significant impact on ship motions and loads acting on the ship [18]. The differences in vertical wave bending moment RAOs between intact and damaged ships are very often ignored and RAOs of the intact ship is frequently used in the safety assessment of

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damaged ships [19]. Forced oscillatory heave tests in calm water were carried out by varying the model-motion parameters and examining both intact and damaged conditions [20] and free-roll decay tests were performed for intact and damaged sections [21] to understand the complex and nonlinear behavior of floodwater inside a damaged ship section.

Despite some researches on the damaged ship behavior in waves has been studied widely, regardless of the studies of damaged ship hydrodynamics are still devoted in order to gain some interpretations of the physical understanding of ship behavior of damaged ship. These are reasonable and interested that almost every year these research topics have been studied as explained previously. Furthermore, although the experimental study of the dynamic motions of a damaged ship in waves had ever been conducted previously [22], the experimental research results are still needed and then these could be used for numerical validation by the research community in future research. Therefore, the present research has described the behavior of heave, pitch, and roll motions of a damaged ferry in head and beam waves through experimental investigation. Here, the flooding ingress of water to compartment has been simulated in various leakage probabilities or scenarios. The extreme bow and stern trim conditions in each scenario in waves were applied for experimental

work.

II. METHOD AND EXPERIMENTAL SET-UP

A. A scenario of Water Ingress

The damaged ship due to a collision or aground has an impact on damage to the ship's compartment. Therefore, the possibility of damage conditions to the ship model was made into several scenarios where water ingress entered into compartment leakages. There are three damage scenarios were made by using a probabilistic approach based on Resolution MSC.429 [23] including one damaged compartment, two damaged compartments, and three damaged compartments. Here, the damaged compartment was considered an asymmetric occurrence, otherwise, it was ignored. The overall damage scenarios into the ship model are shown in Tables 1 to 3. Before applying the damage condition, the ship model was in full load in the initial condition.

In order to predict the volume of water ingress into the damaged compartment, the change of water section vertically and horizontally was captured time by time and closely using a high-speed camera where the deck, compartment, and tank partition were made of acrylic material.

TABLE 1.
ONE DAMAGED COMPARTMENT

Compartment	Volume (cm ³)
SGR	303.120
WBT No.2	593.344
ER	3689.304
VOID No.3	2472.160
VOID No.1	2961.296
WBT No.1	478.760
FPT	621.456
SGR	303.120

TABLE 2.
TWO DAMAGED COMPARTMENTS

Compartment	Volume (cm ³)
FPT + WBT No.1	1100.216
WBT No.1 + VOID No.1	3440.056
VOID No.1 + VOID No.3	5433.456
VOID No.3 + ER	6161.464
ER + WBT No.2	4282.648
WBT No.2 + SGR	896.464
FPT	621.456
SGR	303.120

TABLE 3.
THREE DAMAGED COMPARTMENTS

Compartment	Volume (cm ³)
SGR + WBT No.2 + ER	573.221
WBT No.2 + ER + VOID No.3	844.351
ER + VOID No.3 + VOID No.1	9122.760
VOID No.3 + VOID No.1 + WBT No.1	5912.216
VOID No.1 + WBT No.1 + FPT	507.689

Then, the volume of water ingress could be calculated by using the integral section area of water ingress in the compartment. The ship model was tested firstly in calm water and it was in static and maximum draft conditions. In the ship model, the compartment was leaked in the bottom part and side part. Then, the hole of the compartment was opened based on the scenarios to obtain

the actual trim and draft caused by the compartment leakage. The extreme bow trim tb (-) and stern trim ts (+) conditions on each scenario were applied to head and beam waves for experimental work.

B. Experimental Set-up

The purpose of experimental work is to measure the

motion responses of ship models within water ingress to compartment leakages. Then, the motion responses that were measured are heave, pitch, and roll motions. The model test was conducted at towing tank, Ship Hydrodynamics Laboratory, Naval Architecture Department, Hasanuddin University. The towing tank sizes are 60 m in length, 4 m in width, and 4 m in depth.

A ship model as shown in Fig. 1 is a ferry type and the model body is made of fiberglass material. The body lines plan of the ferry is shown in Fig. 2 and the arrangement of compartments is shown in Fig. 3. The compartments that were arranged on the ship model were similar to the general arrangement of the actual ferry. The diameter of the hole that is assumed as leakage was 0.009 m. Then, the main dimensions of the actual ferry and the model are presented in Table 4. The geometric scale between actual ferry and model was considered 1:50. The model's speed was set at zero speed and the model was placed in the mid of towing tank length to avoid the wave reflection disturbance as illustrated in Fig. 4. The model's position was kept fix during the

experimental process by a post and the post was also kept the model on sway motion. The post was attached on the carriage vertically to the amidship model and it moved freely on heave z , pitch θ , and roll ϕ motions. In the post, the pitching block and the heave potentiometer were attached to the lower post. Moreover, the alignment arms were not attached to the model. A high-speed camera was installed in the carriage structure with any proper technique in order to capture the time progressive of water ingress entering into a compartment.

The towing tank is equipped with a wavemaker. In the presented experiment, the regular waves were applied in two-wave directions that were head and beam waves to the ship model. The wave parameters were measured by using the wave probe installed in the towing tank and connected to the computer device. The wave amplitude ζ_a and length λ that were applied to ship motion was 0.018 m and 0.905 m respectively. The ratio between the wave amplitude ζ_a and the freeboard height F_b of the ship model is 1.50.



Figure 1. Ferry model.

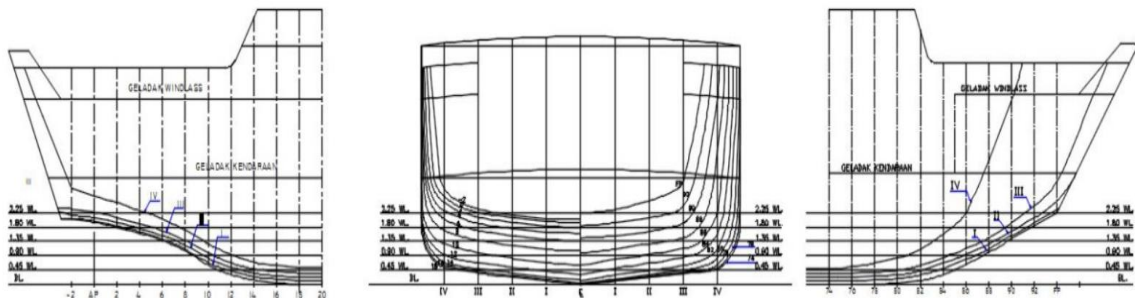


Figure 2. Ferry's lines plan.

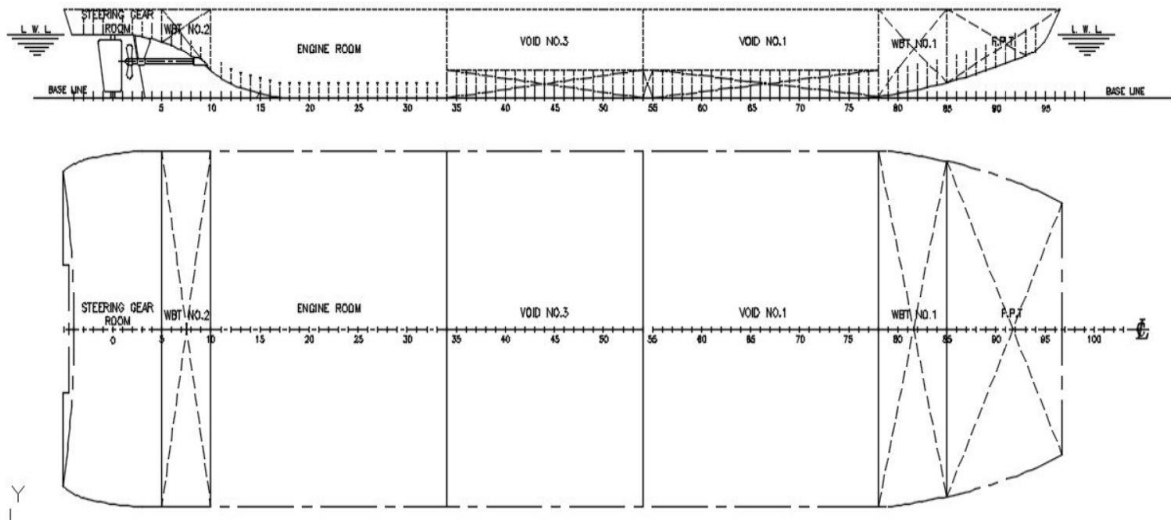


Figure 3. Compartment arrangement.

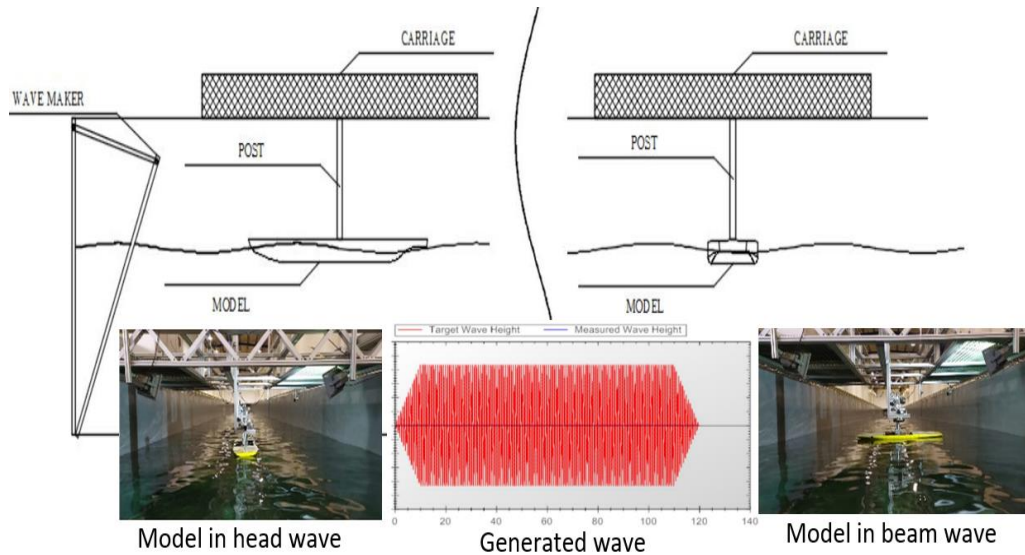


Figure 4. The illustration of the Experiment scheme in towing tank.

TABLE 4.
 MAIN DIMENSIONS OF SHIP AND MODEL

Description	Actual Ship (m)	Model (m)
Length between perpendiculars/ LBP	47.00	0.940
Length Overall/LOA	49.85	0.998
Breadth/B	14.00	0.280
Height/H	3.35	0.067
Draft/T	2.25	0.045

The mathematical model that relates with this presented experimental regarding the motions of damaged ships has been stated in some research accordingly. The floodwater dynamics and their effect on ship motion were modeled [24]. Also, the study of the behavior of damaged ships in waves was studied using the integrated numerical method [10]. Referring to both studies, the equations of motions of the rigid body is governed by the following linear and angular momentum equations as follows:

$$m (\dot{u}_C + \omega \times u_C) = F \quad (1)$$

$$J_C \cdot \dot{\omega} + \omega \times J_C \cdot \omega = M_C \quad (2)$$

where m denotes the mass of the ship, C refers to the center of m , u_C denotes the velocity vector of C , F denotes the resultant vector of external forces acting on the ship, J_C is the tensor of inertia moments of the ship with respect to C , ω is the angular velocity vector of the ship, and M_C is the resultant vector of external moments acting on the ship with respect to C .

Furthermore, Within the framework of potential flow theory [10], the components of external forces and moments can be generalized as follows:

$$F_i = (F_{FK})_i + (F_D)_i + (F_R)_i + (F_G)_i + (F_W)_i, i = 1, 2, \dots, 6. \quad (3)$$

where I denote the components of the external forces or moments (moment understood for $i = 4, 5, 6$), F_{FK} is the Froude-Krylov force, F_D is the diffraction force, F_R is the

radiation force, F_B is the buoyancy force, F_G is the gravitational force, and F_W is liquid load due to the motion of floodwater inside compartments.

III. RESULTS AND DISCUSSION

Ship model with compartment leakage based on the damage scenarios was tested previously in calm water. Then, the condition parameters of the model on each scenario after testing as provided in Tables 5 to 7. Almost all conditions were applied to experimental work however the extreme conditions in the bow trim and stern trim obtained by each damage scenario have been only discussed here.

Table 5 describes condition parameters of the ship model on one damaged compartment where the leakage of the engine room (ER) as shown Fig. 5 and void tank No.1 (Void No.1) as shown Fig. 6. Those conditions impacted full water volume of 3689.3 mm³ and 2961.3 mm³ and took water ingress fully in 75 sec and 322 sec respectively. The draft of the ship model in the bow and stern parts caused by the water flooding was 2.75 cm and 6.14 cm on the leakage of the ER and 5.10 cm and 3.94 cm for the leakage of the Void No.1. For those conditions, the model experienced extreme stern trim (+) 0.034 rad on the leakage of the ER and extreme bow trim (-) 0.012 rad on the leakage of the Void No.1.

For the parameters of the two damaged compartments scenario as shown in Table 6, the leakage of the water ballast tank No.2 (WBT No.2) and steering gear room (SGR) as shown in Fig. 7 simultaneously impacted full water volume of 896.464 mm³ in 84 sec. The water

ballast tank No.1 (WBT No.1) and Void No.1 as shown in Fig. 8 simultaneously were 3440.056 mm³ in 114 sec. Those conditions resulted in the ship model experienced extreme stern trim (+) 0.046 rad on the damaged WBT No.2 and SGR and the extreme bow trim (-) 0.031 rad on the damaged WBT No.1 and Void No.1. These extreme trim conditions were applied to the ship motion experiment as well.

In addition, Table 7 shows condition parameters based on three damaged compartments scenario. In contrast with other scenario results, overall trim parameters in this scenario passed the margin line of the model or experienced water on deck. This means that the ship model would be possible to sink caused by this scenario. Also, this condition is to be attention or consideration on design of compartment and tank arrangement for ferry Ro-Ro. Therefore, the overall of those scenarios was not applied to experimental work.

Figures 9 to 11 show the examples of the time history of heave, pitch, and roll amplitudes for one and two damage scenarios. In the time history of motion, the heaving amplitude is indicated by (+) and (-) directions which mean a vertical up movement and a down movement respectively. The pitch amplitude indicated by (+) direction means a rotational movement to the stern of the ship model, and (-) direction means a rotational movement to the bow of the ship model. Then, the roll amplitude indicated by (+) direction means a rotational movement to the starboard side of the ship

model, and reversely (-) direction means a rotational movement to the port side of the ship model.

Figure 9 shows the time histories of the heaving amplitude (a) and the pitch amplitude (b) within flooding water into ER in the heading wave. The initial center of gravity (CoG) point shifted vertically in a little magnitude to up (+) while flooding water into ER. After shifting the CoG point, the heaving amplitude of the vertical up movement (+) is higher than the vertical down movement (-). Similarly, the CoG point rotated to the stern model around 0.019 rad and then the rotational response tends to stern model (+) within flooding water into ER. The tendency of motion response is influenced by stern trim condition (+), and the wave load directed to the head bow of the model has impacted significantly the progressive water into ER as well as the slosh dynamic to the stern wall (bulkhead). In this scenario, the averaged amplitude of heave and pitch amplitude were obtained 2.17 cm and 0.03 rad respectively. In beam wave, the averaged amplitudes of heave and roll motions were obtained 4.69 cm and 0.09 rad respectively. In this case, the CoG point shifted a little magnitude to down (-) from the CoG point in intact condition. The amplitude in vertical up movement (+) is higher than in down movement (-), and then the rotational movement to the starboard side (+) has the same magnitude with port side (-). However, the CoG point tends transversely to the starboard side. This response is influenced by the sloshing impact, exciting moment, and wave direction to the port side.

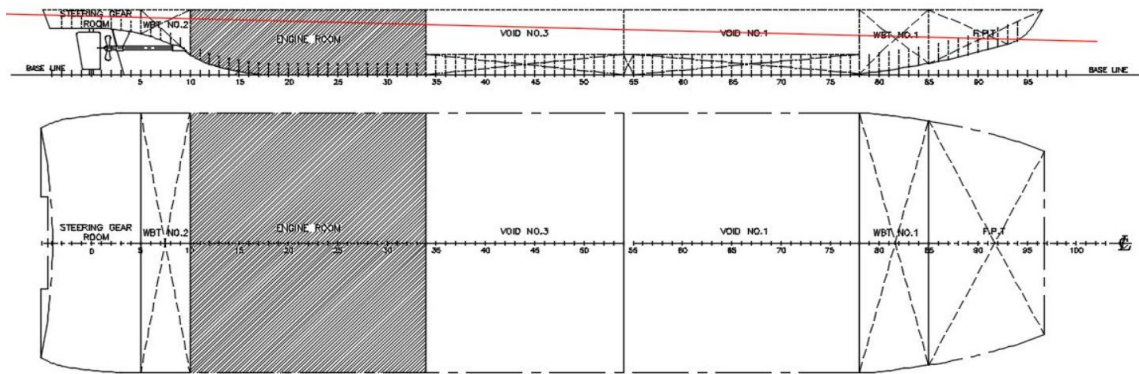


Figure 5. Damaged engine room (ER).

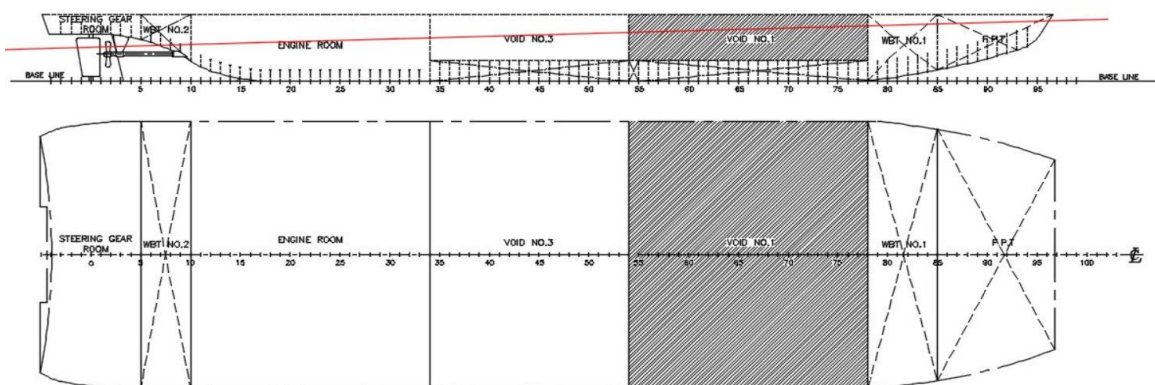


Figure 6. Damaged Void No.1.

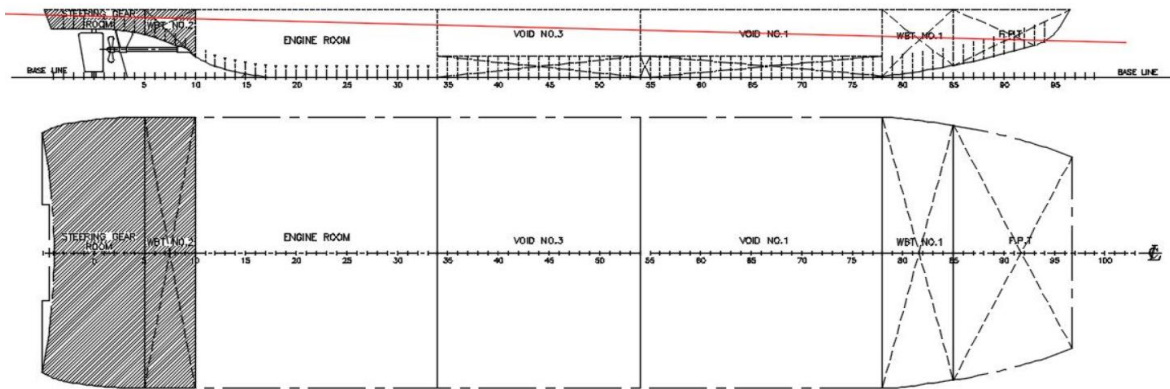


Figure 7. Damaged WBT No.2 and SGR.

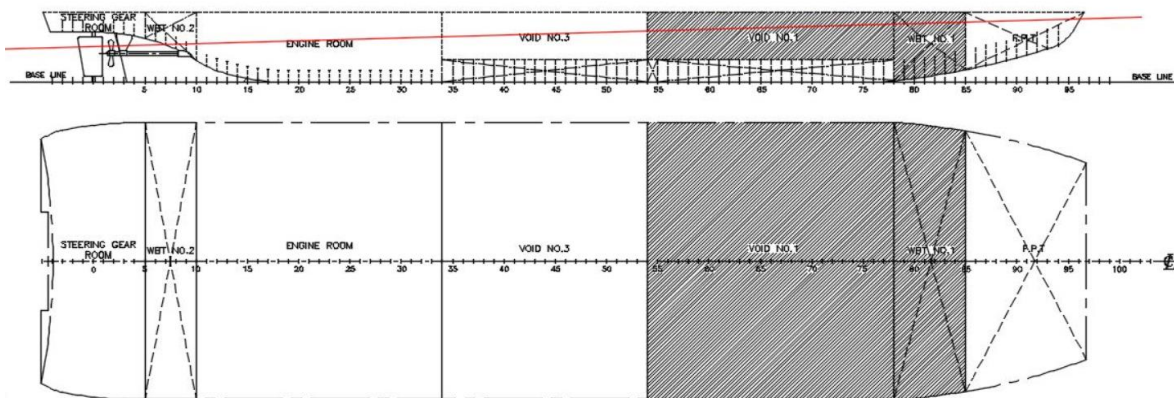


Figure 8. Damaged WBT No.1 and Void No.1.

TABLE 5.
PARAMETERS OF ONE DAMAGED COMPARTMENT

Compartment	Water Vol. (cm ³)	Time of full water ingress (sec.)	Trim (rad.)	Draft (cm)	
				Bow (Tb)	Stern (Ts)
SGR	303.12	23	(+) 0.019	3.50	5.43
WBT No. 2	593.34	54	(+) 0.029	2.98	5.92
ER	3689.30	75	(+) 0.034	2.75	6.14
VOID No. 3	2472.16	236	(+) 0.014	3.75	5.20
VOID No. 1	2961.30	322	(-) 0.012	5.10	3.94
WBT No. 1	478.76	38	(-) 0.002	4.63	4.38
FPT	621.46	43	(-) 0.001	4.45	4.55

TABLE 6.
PARAMETERS OF TWO DAMAGED COMPARTMENTS

Compartment	Water Vol. (cm ³)	Time of full water ingress (sec.)	Trim (rad.)	Draft (cm)	
				Bow (Tb)	Stern (Ts)
FPT + WBT No. 1	1100.22	47	(-) 0.015	5.263	3.788
WBT No. 1 + VOID No. 1	3440.06	114	(-) 0.031	6.075	3.030
VOID No. 1 + VOID No. 3	5433.46	181	(-) 0.016	5.302	3.751
VOID No. 3 + ER	6161.46	102	(+) 0.041	2.393	6.466
ER + WBT No. 2	4282.65	49	(+) 0.043	2.269	6.573
WBT No. 2 + SGR	896.46	84	(+) 0.046	2.125	6.602

TABLE 7.
PARAMETERS OF THREE DAMAGED COMPARTMENTS

Compartment	Water Vol. (cm ³)	Time of full water ingress (sec.)	Trim (rad.)	Draft (cm)	
				Bow (Tb)	Stern (Ts)
SGR + WBT No. 2 + ER	573.22	55	(+) 0.189	Water on deck	
WBT No. 2 + ER + VOID No. 3	844.35	65	(+) 0.313	Water on deck	
ER + VOID No. 3 + VOID No. 1	9122.76	214	(+) 0.076	Water on deck	
VOID No. 3 + VOID No. 1 + WBT No. 1	5912.22	168	(-) 0.069	Water on deck	
VOID No. 1 + WBT No. 1 + FPT	507.69	128	(-) 0.122	Water on deck	

Furthermore, the averaged amplitudes of heave and pitch motions in heading wave for the damaged Void No.1 were obtained 2.50 cm and 0.04 rad, and then the averaged amplitudes of heave and roll motions in beam wave were 5.40 cm and 0.09 rad. In the heading wave, the magnitude of the vertical up movement (+) is higher than the vertical down movement (-), and the rotational movement tends to the bow model (-). On the other hand, the vertical up movement has almost the same magnitude as the downward movement in the beam wave, and then the rotational movement to the starboard side (+) has a higher magnitude comparing with the port side (-).

The heave, pitch, and roll responses are higher on the damaged Void No.1 comparing with the damaged ER. The responses are also influenced by ship conditions

where the volume water ingress and trim level on damaged ER are larger than the damaged Void No.1. Regardless, the damaged compartment in the stern part could degrade ship response, and this case of one damage condition could also reduce the survivability of a ship. This could be a consideration in analyzing one damage condition to design a ship, particularly in ER arrangement.

Despite the volume of water ingress in the stern part caused by the damaged SGR and WTB No.2 is too lower than the bow part caused by the damaged Void No.1 and WBT No.1, the draft of stern trim is higher than the bow trim draft. This is caused by the inertia mass moment where the CoG shifted away and closed to the bow part caused by the damaged Void No.1 and WBT No.1.

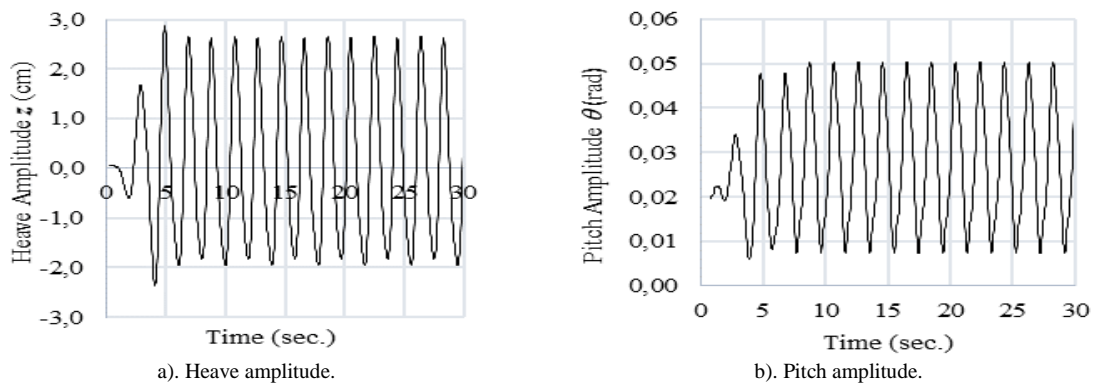


Figure 9. Time history of motion in heading wave within damaged ER.

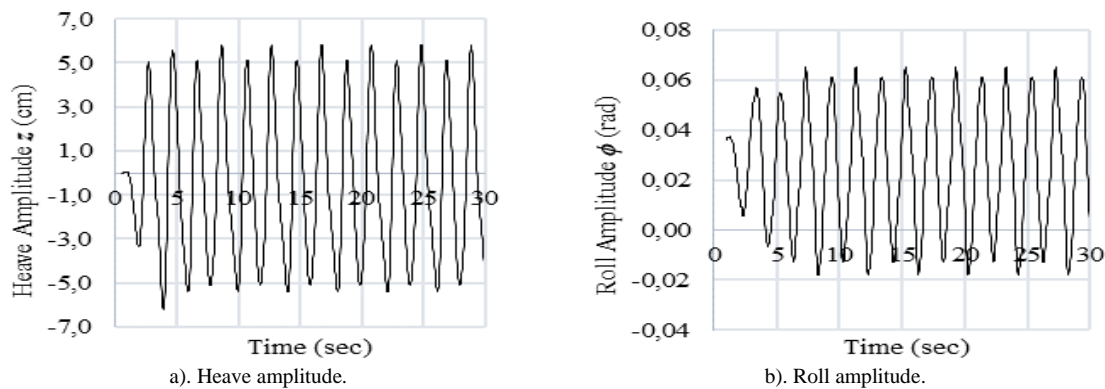


Figure 10. Time history of motion in beam wave within damaged Void No.1 and WBT No.1.

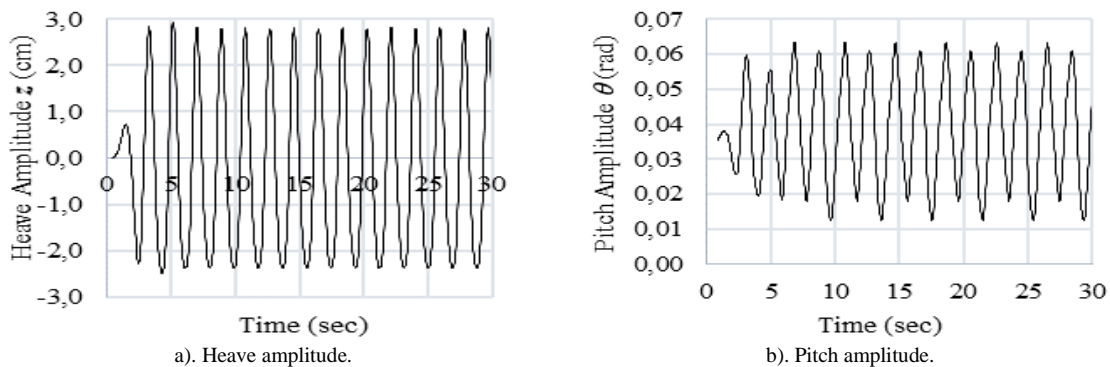


Figure 11. Time history of motion in heading wave within damaged SGR and WTB No.2.

Table 8 shows the averaged response of heave, pitch, roll motions on two damaged compartments

simultaneously. The heave amplitude of the ship model on damaged SGR and WTB No.2 is higher than the

damaged Void No.1 and WBT No.1 in the heading wave, whereas it is lower in the beam wave. In addition, the pitch and roll amplitudes of the ship model on the damaged SGR and WTB No.2 are higher than the damaged Void No.1 and WBT No.1 in head and beam waves respectively. The phenomenon of water on deck was experienced in the case of the damaged Void No.1 and WBT No.1 in the heading wave. This phenomenon influences ship response to be dangerous conditions.

Based on the discussion above, the motions of the damaged ship are influenced by the incorporation of internal, combinatorial, and external factors. The internal factors due to damage conditions impact the increase of inertia mass, the decrease of damped oscillation, and the decrease of restoration ability (buoyancy). The combinatorial factor is the incoming water and the sloshing impact. Then, the external factor is resulted by the exciting wave force and the moment where the magnitude of the exciting wave is similar within the damaged ship in a regular wave.

The behaviors of heave, pitch, and roll motions of the damaged ship are described and characterized by transfer function or response amplitude operator (RAO). The response region of the damaged ship model is assumed in the distance of freeboard Fb from water level (=0 mm) to upper deck level (=0.022 mm). Then, the effect of exciting waves on motion is characterized by non-dimensional wave amplitude and it is defined by increased trim (tb or ts) divided by wave amplitude ζ_a . The increase of trim tb or ts means the flooding water in the damaged compartment on the bow part or stern part respectively.

Figure 12 shows the nondimensional heave response of one damage condition of the damaged ER and the damaged Void No.1 respectively. The nondimensional heave response (heave RAO) is defined by the ratio between heave amplitude z and wave amplitude ζ_a or z/ζ_a .

TABLE 8.
 THE AVERAGED AMPLITUDE OF HEAVE, PITCH, AND ROLL MOTIONS IN TWO DAMAGED COMPARTMENTS

Damaged Compartment	Averaged motion amplitude		
	Heave (cm)	Pitching (rad)	Roll (rad)
Void No.1 + WBT No.1	1.980	0.055	-
Void No.1 + WTB No.1	6.666	-	0.075
SGR + WTB No.2	2.732	0.054	-
SGR + WBT No.2	5.081	-	0.091

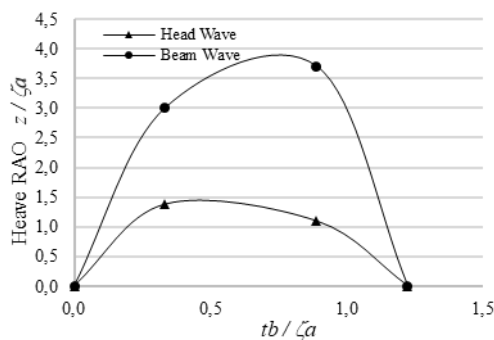


Figure 12. Heave RAO caused by increased bow trim in head and beam wave.

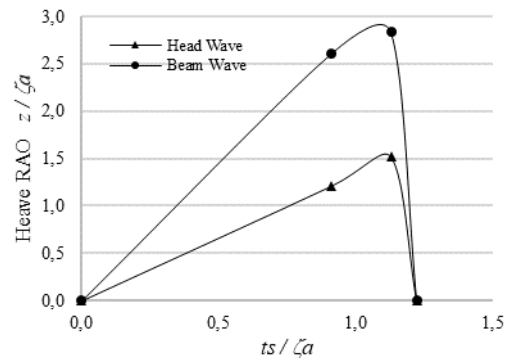


Figure 13. Heave RAO caused by increased stern trim in head and beam wave.

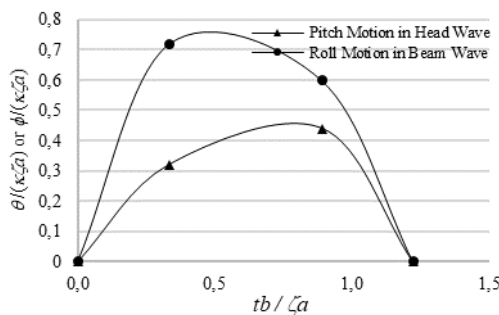


Figure 14. Pitch and Roll RAO caused by increased bow trim in head and beam wave.

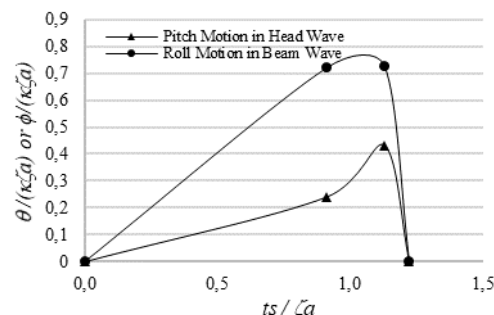


Figure 15. Pitch and Roll RAO caused by increased stern trim in head and beam wave.

For the effect of heading wave on heave motion, the increase of bow trim tb/ζ_a from 0 to 0.5 affects the increase of heave motion, and then heave motion tends to decrease until the water reaches the bow ship deck. In the same wave frequency, the heave motion tends to

increase in increasing bow trim tb/ζ_a from 0 to 0.8, and then it decreases. The heave motion in the beam wave is higher than in the heading wave. The peak resonance of heave motions in bow trim tb/ζ_a occurs at 0.8 in beam wave and at 0.5 in heading wave. However, both of the

peak resonances that affect higher heave RAO is 1.5 in heading wave and 3.89 in beam wave. In order to avoid vulnerable conditions caused by bow trim increase tb/ζ_a or water ingress into a compartment on ship bow part, the resonance regions of heave RAO should be less than 0.2 in heading wave and 0.1 in beam wave.

Figure 13 shows heave RAO caused by the increased stern trim ts/ζ_a . The tendency of both heave RAO in head and beam wave is similar where it tends to increase as linear as in increasing ts/ζ_a , and it decreases around 1.22. The heave response region is less than 1.0 when ts/ζ_a reaches around 0.73 in the heading wave and 0.4 in the beam wave. The response region of bow trim tb/ζ_a is larger than ts/ζ_a . This means the damaged compartment on the stern part of a ship could survive on exciting wave effect comparing with the damaged compartment in the bow part. However, this should be similar in a little damage.

Meanwhile, the nondimensional pitch or roll responses (pitch RAO or roll RAO) is defined by the ratio between pitch amplitude θ or roll amplitude ϕ and incident wave elevation that are $\theta/(k\zeta_a)$ or $\phi/(k\zeta_a)$ where k is wave number $2\pi/\lambda$. These RAOs are described in relation to the nondimensional parameter of increased trim (bow trim tb or stern trim ts) divided by encountering wave amplitude ζ_a that are defined by tb/ζ_a or ts/ζ_a . Figures 14 and 15 show pitch and roll RAOs caused by increased bow trim tb/ζ_a or stern trim ts/ζ_a in head and beam wave. The tendencies are similar to the tendencies of the heave RAO for bow trim and stern trim. The pitch and roll response seem small magnitude within the response region.

IV. CONCLUSION

The experimental work of the motions of the damaged ferry Ro-Ro was successfully conducted. Then the behavior of the responses of the damaged ship is concluded accordingly. For one damage condition, the damaged compartment on ER or Void No.1 affected more extreme stern or bow trim conditions respectively. Then, the two damage conditions of WBT No.2 and SGR in the stern part or WBT No.1 and Void No.1 in the bow part resulted in extreme stern or bow trim respectively. The heave, pitch, and roll responses are higher on the damaged Void No.1 comparing with the damaged ER. Also, the heave, pitch, and roll amplitudes on damaged SGR and WBT No.2 were higher than Void No.1 and WBT No.1.

The peak resonances of heave RAO on bow trim tb/ζ_a affect higher magnitude than on stern trim ts/ζ_a . Pitch and roll RAO caused by increased bow trim tb/ζ_a or stern trim ts/ζ_a in heading and beam wave have a small magnitude within the response region. The ferry Ro-Ro experiences over motions response in beam and heading wave during damage conditions or water ingress into compartment or tank, regardless ferry Ro-Ro must be primarily considered any equipment to reduce those responses.

The notable results describe the motions of the damaged ship are influenced by the incorporation of the

internal, combinatorial, and external factors. The internal factors due to damage conditions impact the increase of inertia mass, the decrease of damped oscillation, and the decrease of restoration ability (buoyancy). The combinatorial factor is the incoming water and the sloshing impact. Then, the external factor is resulted by the exciting wave force and the moment where the magnitude of the exciting wave is similar within a damaged ship in a regular wave.

These behaviors of the damaged ferry Ro-Ro could be considered in order to obtain a proper design such as the design of compartment and tank arrangements, increase of the number of compartments, and design of stern form. Regarding the three damaged compartments, the phenomenon of the water on the deck is possible occurred, and this condition should be attention for regulation purposes.

As known, the interpretations of a damaged ship have been considered recently only in static condition and probabilistic parameters. Furthermore, the static and probabilistic parameters of a damaged ship are not fully guaranteed the ship's survivability. Therefore, the overall prediction of the damaged condition of a ship design would compensate later for the human error in a ship accident.

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