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Investigating the motions' characteristics of a towed barge in extreme heading wave

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Abstract. A towed barge is one of the typical sea transportation systems that is basically composed of towing and towed ships connected to each other by a tow rope. During a towing operation exposed to rough sea condition, the risk of collision and breakage of a tow rope may be high and the consequences serious. This paper describes an experimental investigation of a towed barge's motions in heading waves. The effects of various lengths and the configuration of tow ropes incorporated with various loading conditions of the towed barge have been taken into account. Here, three tow-rope lengths were used, namely 1L, 1.5L, and 2L; meanwhile, the two tow-rope configurations i.e., Straight-Tow (*ST*) and V-Tow (*VT*) models were applied and incorporated with 50% and 100% of the loading conditions of the towed barge. Regardless of the tow-rope models of *ST* and *VT*, the results revealed that the towed barge's motion responses were generally proportional to the increase of the towline lengths and the towed barge's loading conditions. It should be noted here that the *VT* model with 1L tow rope length in the full loaded condition has less RAO of her heave and pitch motions as compared to the other towing arrangements. Merely, this research investigation provides very useful guidance on a ship towing navigation in waves.

1. Introduction

Recently, the sea transport of coal mining using a towed barge has been effective and feasible. However, a barge has a high VCG, shallow draft and low freeboard [1]. Also, the wave load depends on the transportation route and a towed barge cannot avoid this condition where some risks sometimes happen under towing because of waves and severe weather conditions. Therefore, in order to save a towed barge during sailing and towing, a transport method for a towed barge must be planned or arranged properly.

As known, the transport method for a towed barge is affected by some aspects which are taken into account such as the towing tugboat, wave condition, weather condition, towline system (tension, type and length of tow rope). The towed barge and towing ship motions affect tow rope tensions. The distances between the towing ship and the towed barge should be properly arranged because if the towed barge is too far from the towing ship, the towed barge motion is weakly handled. On the contrary, when the distance is too close it could affect the motion of the towing ship. These aspects



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had been investigated in some studies to make some interpretation of a towed barge, towline system, and its motions' characteristics. These interpretations would be used for arranging towing methods properly and safely as mentioned previously. The numerous studies were focused on only a towed barge's motions or towline system; or on the combined motions and towline system in calm water and waves. These were also solved by several kinds of methods such as mathematical method, or experimental method, or computational fluid dynamics (CFD) method.

These studies include Starsmore et al. [2] which investigated the dynamic response of the barge in a random sea. Inoue et al. [3] discussed the course stability of a towed barge with skegs fitted to both sides of the stern in order to improve its course stability performance, and then Tanaka [4] investigated the course stability performance of the towed barge for a wide beam, shallow draft model tested in a towing tank and the effect of skegs on the barge hull's hydrodynamic derivatives. DeBord et al. [5] presented full-scale barge motions' measurement and comparison with a model test. Lee [6] obtained one conclusion on his research that a towrope of unsuitable length would induce hazardous responses in operations and make it impossible to keep a towed barge in an equilibrium position.

Moreover, Dhavalikar et al. [7] developed and implemented the methodology of stability and motion analysis for practical problems of barge transportation, however, this applied to barge transportation with zero forward speed. Zan et al. [8] investigated the effect to sway motion of different tow rope lengths and arrangements for a towed ship in calm water by conducting an experiment. Yoon and Kim [9] simulated coupled dynamic of a tug-towline-towed barge based on the multiple element model of towline. The rolling of a transport barge in irregular seas was performed by Natskar and Steen [10]. Nam et al. [11] also studied towing characteristics of a transportation barge during multi-tug operation, however, those researches were focused on the characteristics of towline tension. The slewing motion of the barge decreased as the length of the towline increased, and this decrease was even greater when a bridle was connected to the towline [12]. Fitriadhy et al. [13] investigated the course stability of a towed ship by using Computational Fluid Dynamics (Flow3D). The effects of different towline length and towing's velocity on sway and yaw motions were investigated. Furthermore, Fitriadhy et al. [14, 15, 16] presented a CFD simulation to investigate sway and yaw motions and towline tension of a ship towing system in calm water incorporated with symmetrical and asymmetrical bridle towline configurations.

Despite all those well-done research studies mentioned, they were only focused on the motions of yaw, sway, and towline tension. It must be noted that investigation of a towed barge's motions is an important consideration not only in calm water but also in waves in order to result in some interpretations and provide very useful guidance on a ship towing navigation in waves. However, investigations of the pitch and heave motions of a towed barge are still rare and necessary. Therefore, this paper describes the investigation of heave and pitch motions of a towed barge through conducting experiments. Several influences on those motions caused by tow rope length, tow rope type, loading condition, and wave condition have been primarily considered in the experimental work.

2. Experimental Set-up and Method

The model test was carried out and all experimental data were obtained at the towing tank, Hydrodynamics Laboratory, Naval Architecture Department, Hasanuddin University. The towing tank was 60 m in length, 4 m in width, and 4 m in depth. The towing tank was also equipped with a wave maker. The speed of the towing carriage was 4 m/sec maximum.

The body plan of the barge is shown in Fig. 1. Then, the main dimensions of the actual towed barge and the model are presented in Table 1. The geometry scale between actual barge and model is 1:65. The model of the towed barge was made of fiberglass as shown in Fig. 2.

There were two tow posts that were used. The towing ship was represented by the towing post attaching on the carriage. The Froude number Fr of the towing ship was set 0.10. Then, the second towing post was attached on the carriage vertically to the amidship model. This second towing post was equipped with pitch and heave measurement devices. In order to make free heave and pitch motions in the model, the second towing post was let to move freely where the pitching block was

attached on lower the second towing post and the heave potentiometer was attached to the second post as well. The distance between the guide wheel blocks has been considered to have sufficient distance to avoid the heave post as a towing post model. Moreover, the alignment arms were not attached to the model for keeping the heave post and the model in free movement. Therefore, the motions of the towed barge model which were measured in this study are heave motion z and pitch motion q . Although sway motion was slightly experienced during experimental work, it was ignored. The scheme of experimental work is illustrated in Fig. 3.

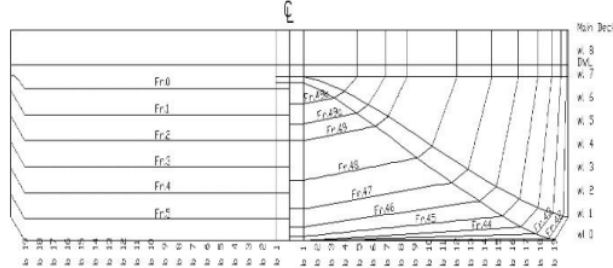


Figure 1. Body plan of the towed barge.

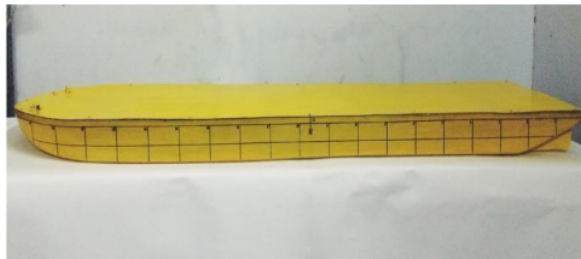


Figure 2. A model of the towed barge made of fiberglass.

The VT-tow shape or L_v was connected to two points on the towed barge and then its length is included in the overall length of the VT-tow rope. The length of L_v used were 0.5L or 0.7 m and they were the same for each lengthening tow rope (1L, 1.5L, and 2L). The length of each tow-rope configuration is presented in Table 2. In the actual condition, a towed barge is sometimes not fully loaded when sailing at sea state. These conditions are also considered in this study. Therefore, the loading conditions of the model were assumed into 50% draft d_1 and 100% draft d_2 and these were then set to the barge draft 0.0351 m (d_1) and 0.0703 m (d_2), respectively.

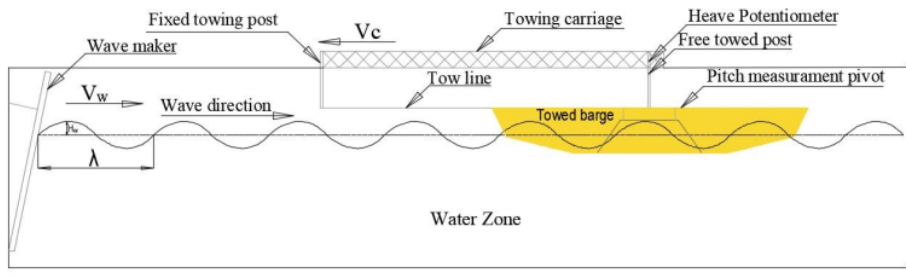


Figure 3. The schematic illustration of the experimental work.

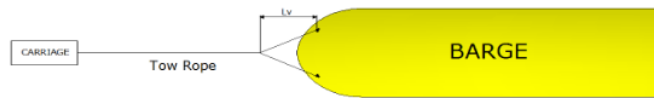


Figure 4. V- tow type (VT).

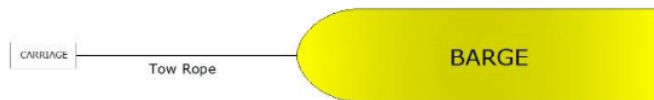


Figure 5. Straight - tow type (ST).

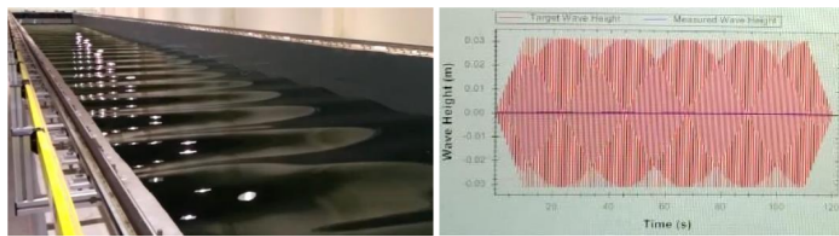


Figure 6. Time history of the wave applied to experiment; wave length 1Lm, wave amplitude 0.03 m.

Table 1. Main dimensions of the actual towed barge and the model.

Dimension	Actual Towed	Model
L (m)	91.44	1.40
B (m)	24.4	0.38
H (m)	5.5	0.09
d (m)	4.57	0.07

Table 2. The length size of tow-rope configurations.

Tow-rope length configuration	Length size	Lv
1L	1.40m	0.7m
1.5L	2.1m	0.7m
2L	2.8m	0.7m

The towing post which was attached to the carriage was located in the front part of the carriage structure. It was connected with tow-rope horizontally to the model. Tow-rope types are determined into 2 (two) types i.e. V-tow VT and Straight-tow ST as shown in Figures 4 and 5, respectively. The tow-rope length is normalized with the length of towed barge model (L) and they are configured into 1L, 1.5L, and 2L. The V-tow type refers to Nelson [17]. Moreover, the Straight-tow refers to Lee [6] and Yang et al. [18].

The regular wave was generated in a towing tank. The wave height was set and assumed as an extreme wave condition. For the first test, the wave was generated by using the wave maker in order to measure its parameters. The wave parameters were also measured by using a wave probe installed in the towing tank and connected to a computer device. The wave amplitude in the range of the wave

period T 1.06 hz was obtained at 0.03 m. The time history of the wave that was applied to the experiment is shown in Fig. 6 where the wave amplitude is 0.03 m and the wave length was 1.4 m or $1L$. The ratio between the wave amplitude z_a and the towed barge freeboard height h ($H-d$) is 1.5. This wave parameter is characterized as a relatively extreme condition.

3. Results and Discussion

In this study, the experimental work of the towed barge in extreme waves was conducted successfully and the heave and pitch amplitudes of the model in the heading wave were measured. Several examples of the time histories of heave and pitch amplitudes which were used as experimental data based on the lengths of tow rope, tow-rope types and loading conditions are shown in Figures 7 to 10, respectively.

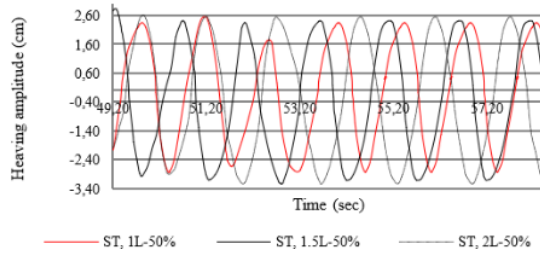


Figure 7. Time histories of heaving amplitude of 50% loading condition and straight tow type (ST).

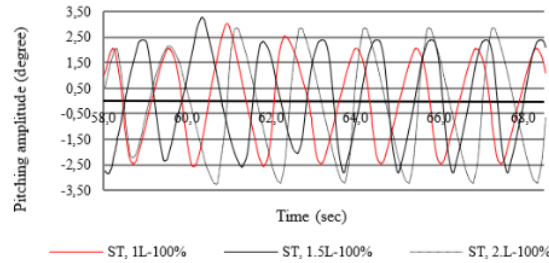


Figure 8. Time histories of pitching amplitude of 100% loading condition and straight tow type (ST).

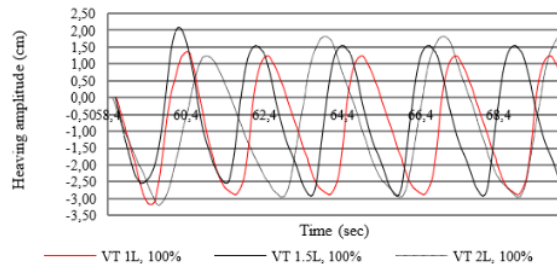


Figure 9. Time histories of heaving amplitude of 100% loading condition and V-tow type (VT).

These were carried out from 0 to 130 sec and then the oscillations of heave and pitch motions were presented only in stable condition from 40 sec to 70 sec. The average heave and pitch amplitudes are presented in Tables 3 and 4.

Figures 7 to 9 show that the heaving and pitching amplitudes are not of the same magnitude in up and down movements through the center gravity point (CG) of the model under extreme regular waves. Most of the times, the heave amplitudes of up movement (+) are lower than down movement (-) through the center gravity point (CG). Moreover, the pitch amplitudes on the bow rotation of towed barge (+) are also lower than that on the stern rotation of the towed barge (-).

In the up movement, all heaving amplitudes are larger than the freeboard height h of towed barge model (0.02 m) for 50% loading condition and then in contrary those seem less than h for 100% loading condition. On the other hand, all heaving amplitudes in the down movement for all loading conditions are bigger than 0.02cm. This means that the loading condition affects up and down movement of a ship. The full load is in better conditions. The influences of the tow rope length and type are further described. The averaged heave and pitch amplitudes for the straight tow rope type and VT type in 50% and 100% loading conditions are shown in Tables 3 and 4.

Table 3. The averaged heaving and pitching amplitudes for the straight tow rope type in 50% and 100% loading conditions.

Straight Tow rope Length (m)	Averaged Heaving Amplitude through CG point (cm)				Averaged Pitching Amplitude through CG point (degree)			
	50% Loading Condition		100% Loading Condition		50% Loading Condition		100% Loading Condition	
1L	+2.37	-2.79	+1.34	-2.21	+2.72	-2.70	+2.07	-2.42
1.5L	+2.41	-3.12	+1.46	-2.42	+2.91	-3.09	+2.41	-2.81
2L	+2.55	-3.45	+1.78	-2.61	+3.24	-3.52	+2.89	-3.29

Table 4. The averaged heaving and pitching amplitudes for the V-tow rope type in 50% and 100% loading conditions.

V Tow-rope Length (m)	Averaged Heaving Amplitude through CG point (cm)				Averaged Pitching Amplitude through CG point (degree)			
	50% Loading Condition		100% Loading Condition		50% Loading Condition		100% Loading Condition	
1L	+2.03	-2.52	+1.12	-2.05	+2.42	-2.63	+2.02	-2.11
1.5L	+2.11	-2.76	+1.35	-2.27	+2.57	-2.78	+2.10	-2.27
2L	+2.43	-2.91	+1.51	-2.45	+3.05	-3.32	+2.23	-2.44

Based on Tables 3 and 4, the towed barge's responses seem to increase with increasing tow rope length and loading condition through CG point for both ST and VT tow rope type. Beside the amplitudes through CG point, the response of the heaving and pitching amplitudes which are through crest to trough of motion cycles seem to increase. Table 3 shows that the lengthening ST tow rope from 1L to 1.5L resulted in an increase of the heaving amplitude of about 7.17% and 9.29% for 50% and 100% loading conditions, respectively. The increased pitching amplitude from 1L to 1.5L was about 10.7% for 50% loading condition and 16.26% for 100% loading condition. Meanwhile, the lengthening tow rope from 1.5L to 2L resulted in an increase of the heaving amplitudes at 8.50% and 13.14% for 50% and 100% loading conditions, respectively. Similar to the result of the lengthening

pitching amplitude of the ST tow rope from 1L to 1.5L, the increase from 1.5L to 2L were about 12.67% and 18.39% for 50% and 100% loading conditions, respectively.

Referring to Table 4, the lengthening VT tow rope from 1L to 1.5L and 2L resulted in increased heaving amplitude by 10.68% and 19.11% for 50% loading condition and then 20.51% and 19.11% for 100% loading condition. In addition, the increase of pitching amplitude for lengthening from 1L to 1.5L and 2L was about 5.94% and 8.97% for 50% loading condition; about 4.36% and 8.35% for 100% loading condition.

It was noted that the lengthening tow rope tended to increase heaving and pitching amplitudes for all tow-rope types and loading conditions. The heaving amplitudes increased significantly from 1.5L to 2L for up and down movement, and in the same condition the pitching amplitudes increased from 1.5L to 2L as well for bow and stern rotation.

The above discussion highlighted that the lengthening tow rope affected all lengths. In this study, the tow rope tension was not considered although the tension of the tow rope is also very influential for controlling and guiding the movement of the ship. Regardless, the tow rope type of the VT was found better than ST and the loading condition of 100% could reduce the towed barge's responses.

Correspondingly, a nondimensional parameter which describes the towed barge's response in extreme waves is characterized by transfer function or response amplitude operator (RAO). This RAO is defined by the response amplitude variable divided by the encountering wave frequency. This RAO could describe motion behavior of the towed barge's response in lengthening tow rope and loading condition for both ST and VT tow rope type associated with extreme wave condition. The nondimensional parameter of heaving motion (heave Response Amplitude Operator/RAO) is given by the ratio between heaving amplitude z to wave amplitude ζ_a or z/ζ_a . Then, the nondimensional parameter of pitching motion (pitch RAO) is characterized by the ratio between pitching amplitude θ to wave amplitude ζ_a and wave number $2\pi/\lambda$ or $\theta/(\zeta_a * 2\pi/\lambda)$. The nondimensional parameters of the heaving and the pitching motions of the towed barge for both ST and VT tow rope type are shown in Figures 10 and 11.

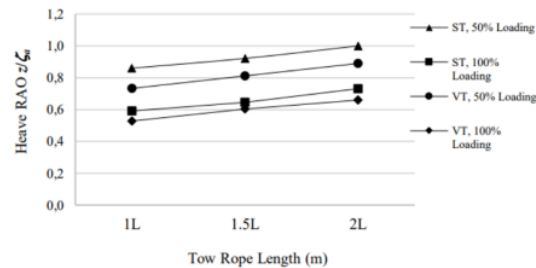


Figure 10. The heave RAO of the towed barge for both ST and VT tow rope type.

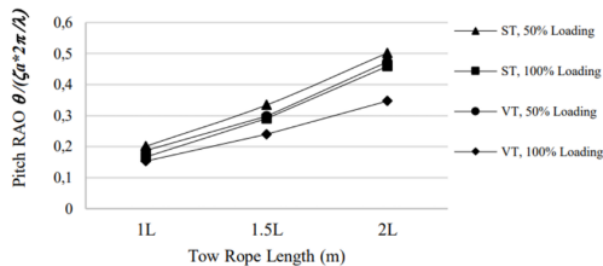


Figure 11. The nondimensional pitching motion of the towed barge for both ST and VT tow rope type.

The heave and pitch RAOs tend to increase with increasing tow rope length for overall loading conditions and tow rope types as expressed in Figures 10 and 11 respectively. All 50% loading condition for both ST and VT tow rope type contributes high heave and pitch RAO in increasing tow rope length and the heave RAO of the ST type is highest in 2L tow rope length at 1.0 and the pitching response is at 0.5. Also, this seems to be the effect of the loading condition toward the heave and pitch RAO. Therefore, the heaving and pitching response could be decreased due to loading condition. For ST type, the loading condition from 50% to 100% decreased heaving response by an average of 27.0% and pitching response by an average of 13.0% in every lengthening tow rope. Moreover, for VT type, the heaving response decreased by 26.0% and the pitching response was given by 13.0% in lengthening tow rope. From this explanation, it could be interpreted that the loading condition affected heaving and pitching response more significantly than tow rope type.

The influence of loading condition was dominantly contributed by the heaving and pitching response compared to the tow rope type and length. In fact, almost all cargo ships including towed barges sometimes sail at sea in full loaded condition and even in overload condition. Regardless, the tow rope type and length are also important considerations to reduce and control heaving response. In this case, the VT type and 1L tow rope length (full loaded condition) is better considering that the lowest Heave RAO about 0.53 and pitch RAO is about 0.15.

The VT type gave better resonance during the towing process than the ST type. In addition, the small length of the tow rope that is 1L gave a small response. However, this might be due to the effect of rope tension. The use of various lengths of the shape L_v of the VT type should be considered for future work. This research can also be developed associated with maneuvering problems.

4. Conclusions

The experiment of a towed barge in wave, with different tow-rope type, tow-rope length, and loading conditions, was successfully performed in the towing tank of Hydrodynamic Laboratory, Naval Architecture Department, Hasanuddin University. The heaving and pitching responses were also important considerations for arranging towing methods. Therefore, the characteristics of the towed barge in waves were found.

The heave amplitudes of the towed barge of up movement (+) were found to be lower than down movement (-) and the pitch amplitudes on the bow rotation (+) were also lower than those on the stern rotation (-) through the center gravity point (CG). In addition, the towed barge's responses increased with increasing tow rope length from 1L to 1.5L and 2L and with increasing loading condition from 50% to 100% for both ST and VT tow rope type.

With several aspects as consideration for arranging towing method, the loading condition affected heaving and pitching response more significantly than tow rope type and length do, however the tow rope type and length were also important considerations that could reduce and control heave RAO.

Finally, the VT type and 1L tow rope length for fully loaded condition was found to better in that it affected the least heave and pitch RAOs. Correspondingly, this study will be extended take into account more various of wave height and wave length to obtain the proper interpretation of motion behaviors of a towed barge in waves. Moreover, our study can also be developed to conduct maneuvering problem and rope tension in the future experimental work.

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