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EXPERIMENTAL STUDY ON HEAVE AND PITCH MOTION CHARACTERISTICS OF A WAVE-PIERCING TRIMARAN

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Summary

Dynamic behaviour of a trimaran vessel is investigated in this study. The body of the trimaran is composed of a centre hull with a quite slender wave piercing bow profile (a length-to-width ratio of 12.96) and two outriggers with Wigley mathematical body forms. Several seakeeping tests are conducted on the model of the trimaran vessel in a towing tank in order to study its heave and pitch motions at different Froude numbers of 0.2, 0.37, and 0.51. Generated waves in the towing tank are of regular type with the wave length changing from 0.6 m to 2.4 m by an increment of 0.3 m. Amplitude of the waves is equal to either 25 mm or 35 mm. A resonance peak can be detected on the curve of the heave response amplitude operator (RAO) versus nondimensional wave length of around 1.0. Increasing the Froude number leads to rapidly descending post-resonance-peak regions of the heave RAO-nondimensional wave frequency diagrams. Changes in the value of the pitch RAO versus nondimensional wave lengths of less than 0.8 are not so sensitive to the changes in the values of Froude number and wave amplitude. Also, for the values greater than 2.5 to 2.8 of the nondimensional wave frequency, the pitch RAO does not experience any significant changes as a result of variations in the Froude number or wave amplitude.

Key words: *Wave piercing trimaran, heave, pitch, model test, experiment*

1. Introduction

In the last thirty years, there has been a significant increase in the use of multi-hull vessels for various applications such as transportation of passengers and/or cargos, fishing, sporting, and oceanography. Features such as high length-to-beam (L/B) ratio for each of the hulls in a multi-hull vessel and also, the hull fine angles of entrance to minimize overall resistance together with the distances between the separated hulls, lead to the fact that the motion characteristics of a multi-hull vessel be quite different from those of a mono-hull. Therefore, to ensure safe seakeeping behaviour of multi-hulls, their dynamics is to be investigated carefully. One of the main reasons for studying the seakeeping of marine vessels is to calculate the vertical acceleration level for the operability of crew and equipment.

Within the last two decades, extensive research has resulted in the development of numerical, experimental and analytical methods for the prediction of resistance and motions of catamaran hull forms. Cook et al. [1] built an eight-metre research catamaran named "Educat" and then instrumented it with a system of strain gauges and motion sensors. They presented their findings on the calibration of "Educat", results of the sea trials and towing tank tests and also correlation of the data with the numerical models. Guedes Soares et al. [2] described the results of model tests on a catamaran in regular waves. They measured some quantities including the heave, pitch, and roll motions, the relative motions at the bow, the vertical accelerations, and the mean added resistance in waves. The effects of the heading angle and also the Froude number on the catamaran behaviour were investigated. It was found that the vertical responses tend to be slightly higher for head waves than for bow waves, but the differences are small. Besides, the vertical responses were found to be very sensitive to the Froude number: they increase with the Froude number. McGoldrick [3] tried to develop a relation between the main parameters of catamaran hull forms and the results of heave and pitch motions in irregular waves. He used the strip theory and his own calculations to assign the added mass. The damping and restoring coefficients are based on the Slender Body Theory using the SEAKEEPER software (FormSys, [4]). Fang and Chan [5] presented the motion characteristics of high-speed catamarans travelling in waves based on two mathematical models: three dimensional translating-pulsating source distribution techniques and three-dimensional pulsating source distribution technique. Bruzzone et al. [6] performed a nonlinear seakeeping analysis on a catamaran hull with a central body of revolution advancing in head regular waves. Behaviour of a fast catamaran in the calm water and also its seakeeping characteristics were investigated experimentally by Broglia et al. [7].

However, in the recent past, a strong interest in the development of trimaran hull forms was shown. Slender centre hulls may cause instabilities in either static or dynamic states of the vessel motions. Such instability problems can be resolved by using two outriggers or side hulls on both sides of the vessel. The outriggers can be located at different longitudinal positions regarding the main hull, although their distance from the main hull can be adjusted accordingly. Investigations have shown that little research has been conducted on such hull forms to reduce their motions. Begovic et al. [8] carried out numerical and experimental research on the hydrodynamic resistance of some realistic hull forms of a high speed trimaran operating in the F_n range of 0.8-1.0. Kurultay [9] analysed numerically the seakeeping response characteristics of a typical trimaran with a variable separation ratio (the ratio of the lateral distance between the centre hull and the side hull to the length of the ship) and with different longitudinal positions of the side hulls. Heave and pitch motion response amplitude operators were evaluated for bow, bow quartering, and beam waves in irregular seas at various ship forward speeds. The motion behaviour of a frigate-type trimaran was studied by Pastoor et al. [10]. They conducted a series of model tests for the frigate-type trimaran. Frequency and time-domain linear and nonlinear hydrodynamic calculations were validated against the model tests. The overall seakeeping behaviour and design load assessments for trimaran vessels were also discussed. Also, Begovic et al. [11] presented the results of a research program carried out on different trimaran hull forms and configurations suitable for medium size fast ferries. They conducted resistance tests on large size scale models of two different hull forms of the main hull and outriggers, both isolated and combined in different configurations. The tests were carried out at the towing tank at the University of Naples. For each isolated hull and trimaran configuration, the total resistance and running trim were assessed. Wave pattern analysis was also performed by experimental tests and by numerical computations, so that the influence of each resistance component was highlighted. Hebblewhite et al. [12] investigated the effects of the (longitudinal) stagger of the side hulls on the motions in heave and pitch of a representative trimaran hull. To quantify the effects of longitudinal stagger of the side hulls (outriggers) with respect to the centre hull, they conducted experimental investigations for four different longitudinal stagger positions. Their investigations demonstrated that this variation and the resulting variation in the radius of gyration could have a significant effect on the heave and pitch motions. Ogawa [13] developed a practical method for the prediction of wave loads acting on multi-hull ships taking into account their side hulls. Also, Mynard et al. [14] performed numerical and experimental investigations into the wave resistance of a systematic series of high speed trimaran hull forms. The hydrodynamic flow interference between the centre hull and the side hulls of trimaran ships, which has a major influence on the total power and also on the positioning of the side hulls, was assessed by Mizine et al. [15]. Onas and Datla [16] were those who used experimental hydrodynamics to validate the numerical prediction of nonlinear roll motions of a frigate-type trimaran in waves.

In a further attempt, Begovic et al. [17] presented a pentamaran hull form suitable for medium distance routes. The main hull and outriggers were of high speed displacement slender hull forms. They evaluated hydrodynamic characteristics and powering performances of the pentamaran hull form and then optimised it with the aid of experimental tests that were performed for different positions of the outriggers.

The literature survey indicates that, to date, investigations on trimaran hull forms have been confined to determining the effects of transverse and longitudinal positions of the side hulls mainly on the resistance and powering characteristics. The present study focuses on the dynamic behaviour of a trimaran vessel. The body of the considered trimaran is composed of a centre hull with a quite slender wave piercing bow profile (a length-to-width ratio of 12.96) and two Wigley-type outriggers. Heave and pitch motions of the trimaran are studied herein at different Froude numbers of 0.2, 0.37, and 0.51 in a towing tank. Regular waves with the wave length changing from 0.6 m to 2.4 m by an increment of 0.3 m are generated in the towing tank. Amplitude of the waves is equal to either 25 mm or 35 mm. Obtained results are explained and discussed in what follows.

2. DESCRIPTION OF THE MODEL

Wave piercing bow profile (Figure 1) improves the hydrodynamic performance of vessels and also simplifies their construction process [18-19]. Other advantages in the construction process of wave piercing bow profiles in comparison with the bulbous bows may be itemized as a decrease of 15% in labour engagement in the construction process, a decrease of 50% in the assembly, welding, and bending expenses (due to the simplicity of this bow type), and a decrease of 15% in works required for the alignment process. And finally, there is a capability of being automatically welded as an additional advantage [18-19].

Fig. 1 Wave piercing bow profile of the centre hull (main hull)

In addition, wave piercing bow profile has so many significant hydrodynamic and efficiency characteristics, including a more energy-efficient shape in waves, higher transit speed, reduced power consumption, improved fuel efficiency, increased operational time, increased schedule-keeping, elimination of slamming and bow impact, soft entry in waves, less spray, low acceleration levels, reduced vibration levels, increased comfort and available crew rest time, safer workplace due to smoother motions and protection provided by the hull [18-20].

The model is made of fibre reinforced plastic with a scale factor of 1/80 according to ITTC 7.5-01-01-01. The hull form was modelled up to the main deck level and no appendages were fitted. Length between perpendiculars and the service speed of the vessel are equal to 124 m and 25 knots, respectively. These features correspond to the *Froude* number of 0.368. Figure 2 shows a transverse sectional view of the main hull and its supporting side hulls. Table 1 presents the main particulars of the prototype vessel and its scaled model, while the body lines are shown in Figure 3.

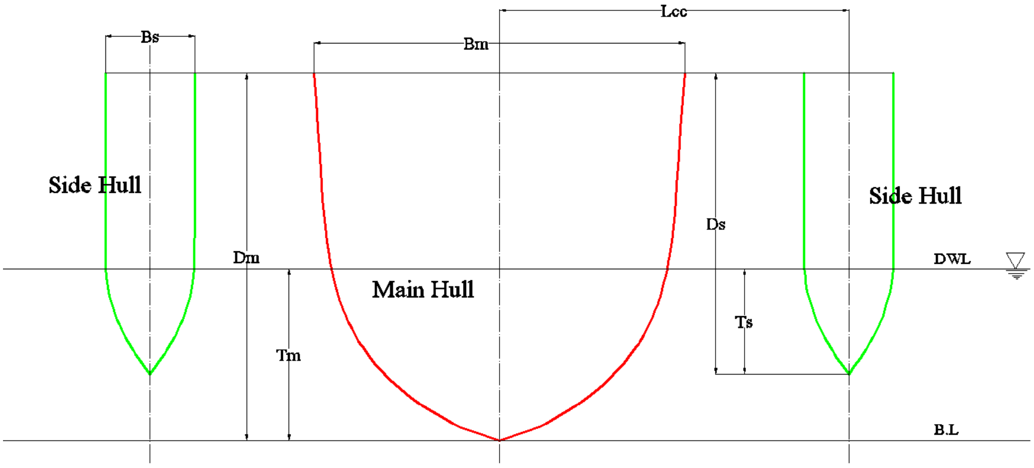
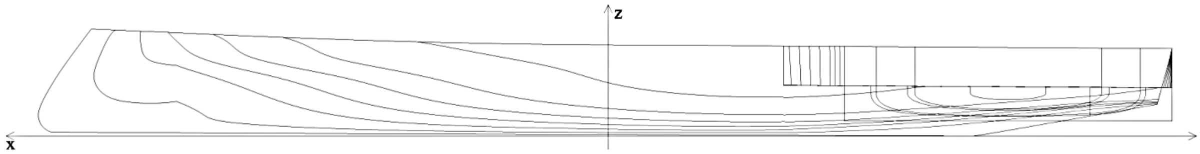


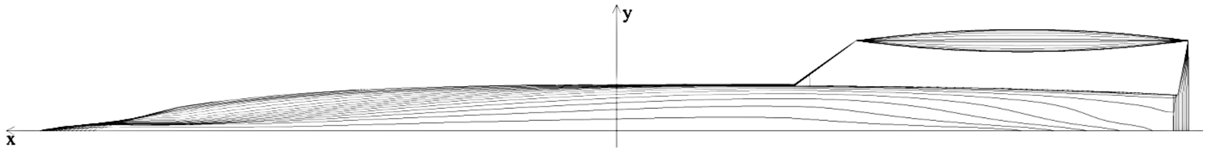
Fig. 2 Transverse sectional view of the main hull and its supporting side hulls

Table 1 Main particulars of the prototype trimaran and its scaled model

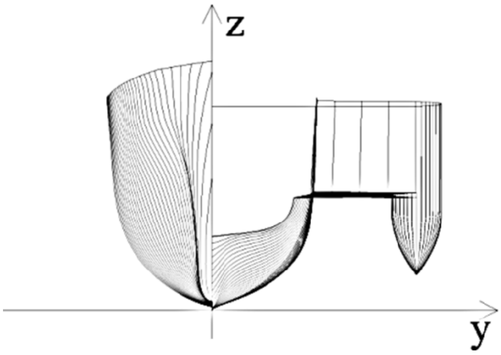
Particular /unit	Prototype	Model
Length overall /m	124	1.55
Length on waterline /m	123.2	1.54
Beam overall /m	21.776	27.22×10^{-2}
Beam on waterline /m	9.6	12×10^{-2}
Depth /m	11.776	14.72×10^{-2}
Draught /m	4.384	5.48×10^{-2}
Length of side hull /m	36	45×10^{-2}
Beam of side hull /m	2.36	2.95×10^{-2}
Depth of side hull /m	8.136	10.17×10^{-2}
Draft of side hull /m	74.4	0.93×10^{-2}
Clearance between centreline of main and side hull /m	9.7	12.125×10^{-2}
Displacement /ton	2248.81	4.39×10^{-3}



(a) Sheer Plan



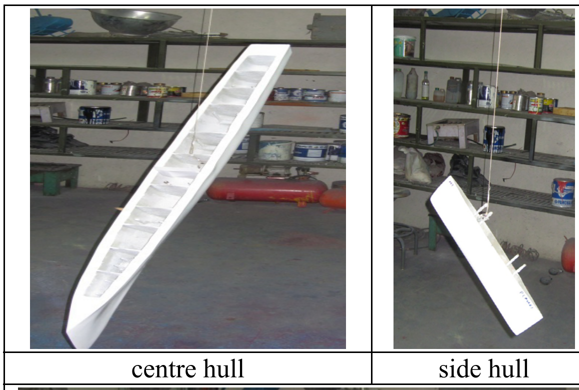
(b) Half Breadth Plan



(c) Body Plan

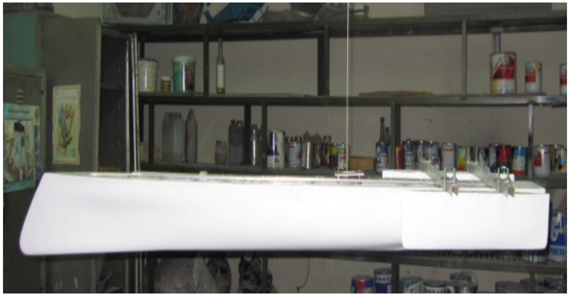
Fig. 3 Body lines and general layout of the trimaran vessel and its scaled model

The model has been built up to the main deck omitting the shaft, propeller, steering and propulsion systems. In order to separate inertia forces from hydrodynamic forces, draft and trim values must be adjusted before each test to compensate for the distribution of weight and inertia forces in the model. Thus, the location of the centre of gravity and also the values of radii of gyration are to be known.



centre hull

side hull



trimaran model

a)

b)

Fig. 4 (a) Application of the suspension method for determining the centre of gravity of the model, (b) Application of the Biffilar method for the determination of radii of gyration

Loading and ballasting procedures of the model are such that the values of Vertical position of Centre of Gravity (VCG), Longitudinal position of Centre of Gravity (LCG) and also radii of gyration for both pitch and roll motions can be reached easily.

Location of the centre of gravity for the model was determined using the suspension method, Figure 4(a). Besides, the Biffilar method [21] was used for the determination of radii of gyration in the air, Figure 4(b). Radius of gyration is found to be equal to 0.387 m for a pitch motion (about 25 percent of water line length) and 0.095 m for a roll motion (about 35 percent of overall beam).

Fig. 5 Towing tank facilities of the Marine Research Centre (MRC) at the Sharif University of Technology (SUT)

3. EXPERIMENTAL SET-UP

The experimental program was performed utilizing the towing tank facilities of the Marine Research Centre (MRC) at the Sharif University of Technology (SUT), Figure 5. The towing tank is made up of three basic facilities: the tank, the computerized towing system and the wave generator. Length and width of the tank are 24 m and 2.5 m respectively (see Table 2). The wave generator is able to produce either regular or irregular waves with a length of 0.3 m to 2.8 m and the maximum amplitude of 0.1 m. There exists a wave damper for damping the waves at the end of the tank. Software developed in the Labview is used to acquire the measured hull motions.

Table 2 Main particulars of the towing tank of the Marine Research Centre (MRC) at the Sharif University of Technology (SUT).

Length×Width×Depth of the tank	Maximum speed of carriage	Maximum acceleration of carriage	Towing system
25 m× 2.5 m× 1.2 m	6 m/s	2 m/s^2	Electromotor (4 kW)

Figure 6 shows the Right handed Cartesian coordinate system located at the centre of gravity of the model. Amplitudes of linear and angular motions of the vessel are represented by η_1, η_2, η_3, η_4, η_5 and η_6. The model is connected to the carriage at its centre of gravity. Except for the heave and pitch motions, the model is not given other degrees of freedom. As Figure 7 shows, the carriage benefits a proper mechanism for the rotation of the model to be adjusted at different heading angles. Before the beginning of any run of the tests, calibration of all of the facilities should be performed and all of the measurement systems are to be set to zero. Using some sensors installed on the mechanism, different parameters including wave height heave and pitch motion amplitudes and the carriage velocity can be measured.

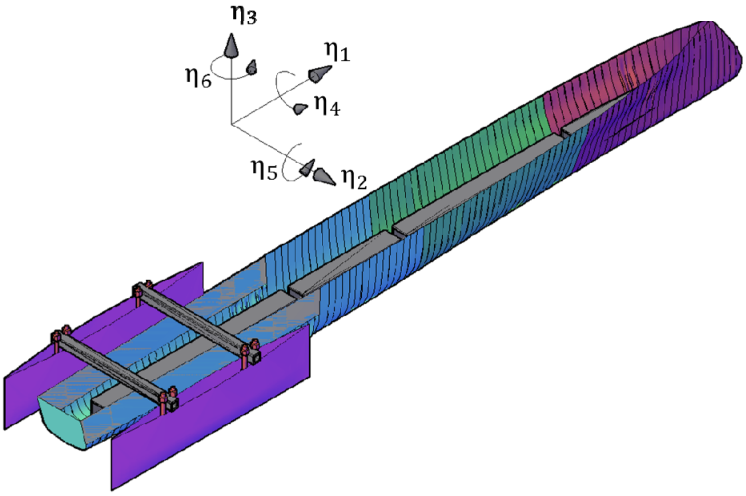


Fig. 6 Notations and sign conventions for ship motion description

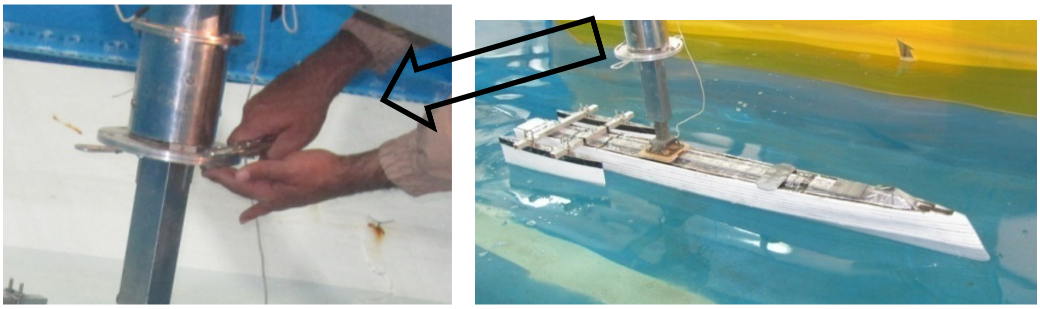


Fig. 7 Mechanism for connecting the model to the carriage and corresponding adjustable device

4. EXPERIMENTAL PROGRAM

A series of seakeeping tests in regular waves is conducted on the trimaran model in order to identify its dynamic behaviour. Considering the displacement of the prototype vessel (2248 ton), the displacement of the model is determined. Other conditions such as trim and draft are so established that the real design conditions of the vessel are fulfilled. Maximum speed of the model is equal to 2 m/s corresponding to the speed of 35 knots of the prototype vessel. In total, 42 different tests representing 42 conditions are carried out. A brief summary of the characteristics of the tests is presented in Table 3, while Figure 8 shows a typical testing situation. F_n and λ are the values of the Froude number and wave length, respectively.

Table 3 Characteristics of the test program

	F_n=0.2		F_n=0.37		F_n=0.51	
λ /m	Amplitude /mm		Amplitude /mm		Amplitude /mm	
	25	35	25	35	25	35
0.6	√	-	√	-	√	-
0.9	√	√	√	√	√	√
1.2	√	√	√	√	√	√
1.5	√	√	√	√	√	√
1.8	√	√	√	√	√	√
2.1	√	√	√	√	√	√
2.4	√	√	√	√	√	√

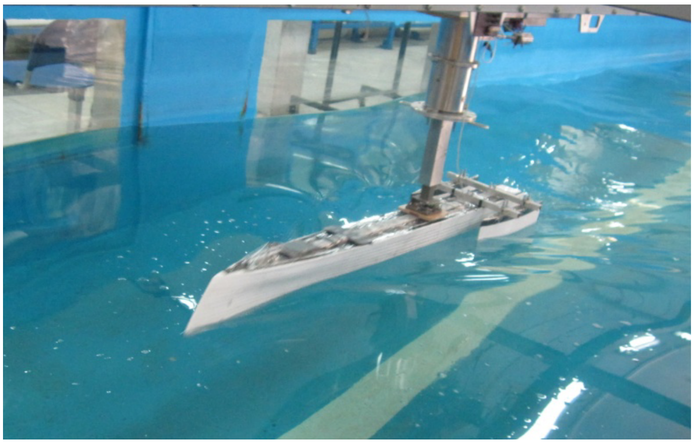


Fig. 8 Model during the seakeeping test under head sea condition (model speed=1.44 m/s, wave length=1.8 m, amplitude=25 mm)

Every test is repeated 3 times to assure the validity of test results. In order to make sure that the water surface has calmed down, tests are carried out with 15 minute delays and the water surface is additionally visually controlled.

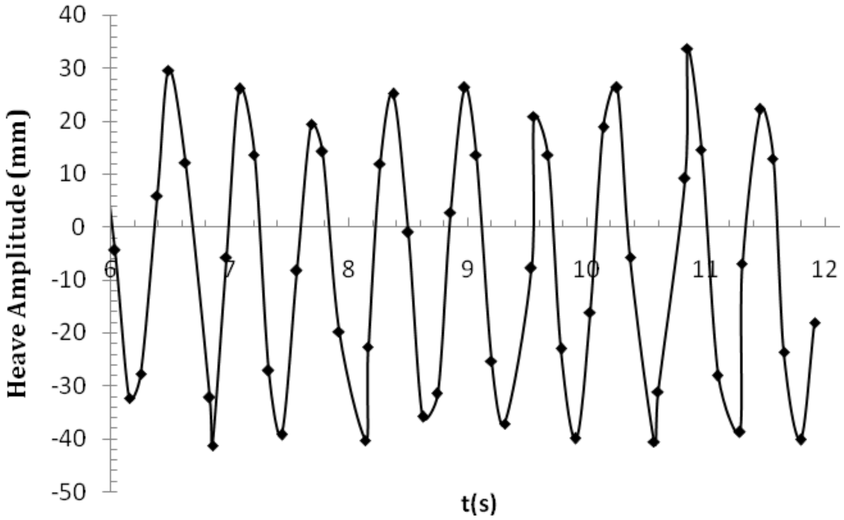
5. RESULTS AND DISCUSSIONS

Experiments are carried out according to Table 3 in order to capture the main characteristics of the heave and pitch motions of the model, while the acquired data is analysed within either time or frequency domains. The rate of sampling for the data acquisition was 50 samples/s. Waves generated in the towing tank are of regular type with the wave length changing from 0.6 m to 2.4 m by an increment of 0.3 m. The amplitude of the waves is either 25 mm or 35 mm. It should be noted that the steepness of the waves employed in the experimental program was small enough to involve some modest nonlinear effects.

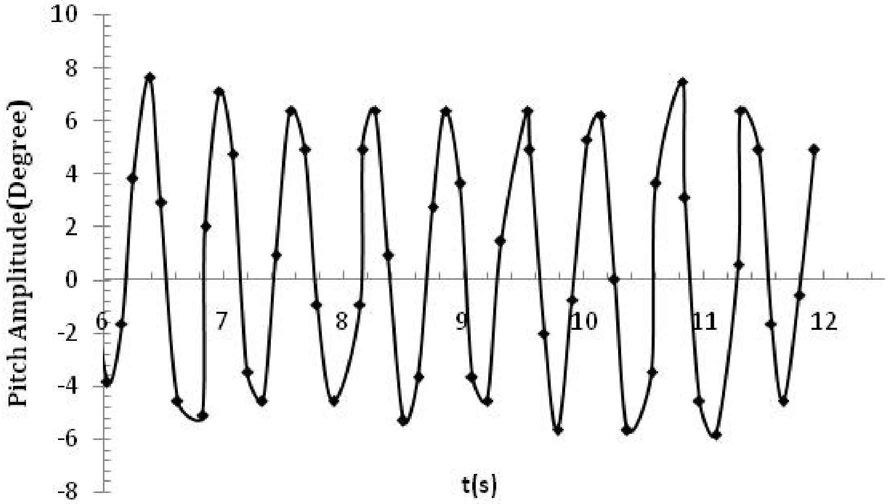
Amplitudes of the heave and pitch motions measured during the towing of the model at the speed of 1.44 m/s, wave length of 1.8 m and wave amplitude of 25 mm are given in Fig. 9. The data shown in Fig. 9 are related to the steady-state zone of the measurements on which further assessments and explanations will be provided in the next sections.

Results of the tests are used to produce transfer functions for heave and pitch motions. The transfer functions are non-dimensional and are called Response Amplitude Operators (RAOs). Each response is represented by its RAO. The RAO is defined by the first harmonic of response divided by the first harmonic of the incident wave elevation. Other terms besides the wave elevation may be used to nondimensionalise the responses.

η_3 / ξ_3 is equal to the heave RAO, while $\eta_5 / (k\xi_3)$ is equal to the pitch RAO. Both values of the heave and pitch RAOs can be drawn against the encountering wave frequency (ω_e) or the encountering wave length (λ). ξ_3 is the wave amplitude, η_3 is the heave amplitude and η_5 is the pitch amplitude. Also, k is the wave number which equals to $2\pi/\lambda$. λ is also the wave length.



(a)



(b)

Fig. 9 Amplitudes of the heave and pitch motions measured during the towing of the model at the speed of 1.44 m/s, wave length of 1.8 m and wave amplitude of 25 mm

5.1 Effects of wave length on the heave motion characteristics

Tests for the Froude numbers of 0.2, 0.37, and 0.51 are conducted in wave lengths between 0.6 meters and 2.4 meters, see Table 3. Based on the test results, curves of the heave RAO versus nondimensional encountering wave length have been drawn for 2 different values of the wave amplitude, 25 mm and 35 mm, which are shown in Fig. 10.

A resonance peak can be detected on each of the curves shown in Fig. 10. The peak resonance occurs around λ / L_{wl} =0.98 for the case of lower Froude numbers, i.e. F_n=0.2 and F_n =0.37, irrespective of the value of wave amplitude. Also, for the case of F_n=0.51, the peak resonance occurs at λ / L_{wl} =1.18, when the wave amplitude is equal to either 25 mm or 35 mm.

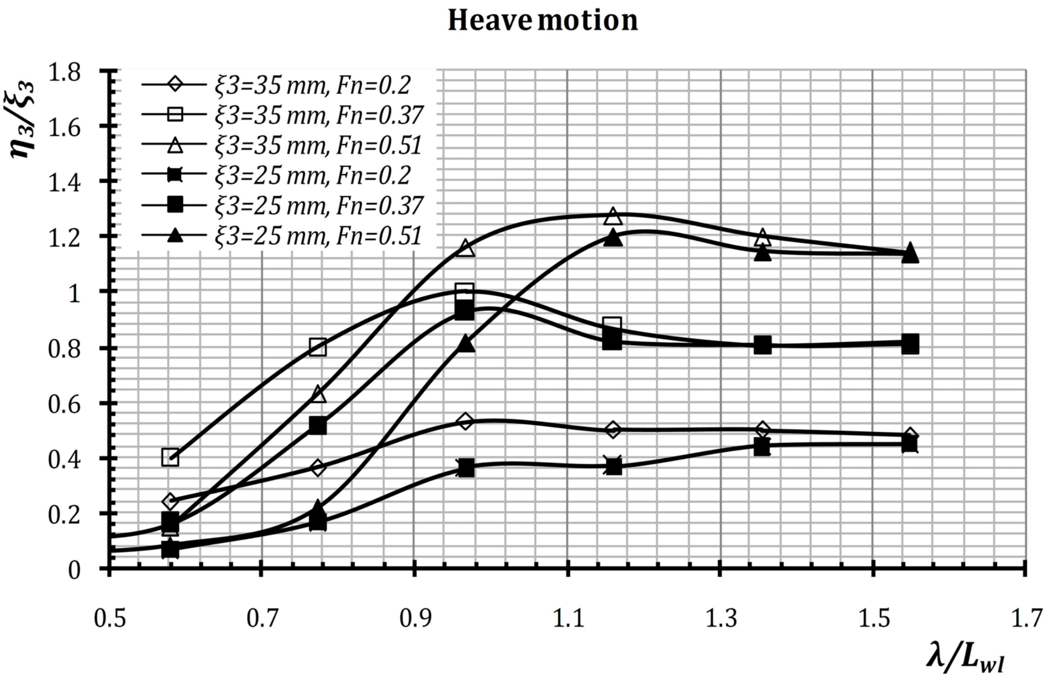


Fig. 10 Heave RAO as a function of nondimensional encountering wave length for the trimaran at different Froude numbers for the cases of wave amplitude equal to 25 mm and 35 mm

After reaching the resonance regions in Fig. 10, the heave motion tends to be constant as the wave length increases. This constant value of heave motion is directly related to the vessel speed. The heave RAO in the post-resonance region is equal to 0.45, 0.82, and 1.1 for the Froude numbers of 0.2, 0.35, and 0.51, respectively. This shows the effect of the vessel speed on its heave motion.

5.2 Effects of wave frequency on the heave motion characteristics

Figure 11 shows the relationship between the heave RAO and nondimensional encountering wave frequency, for two cases of wave amplitude to be equal to either 25 mm or 35 mm, respectively. When the wave amplitude is equal to 25 mm, a resonance peak can also be identified for nondimensional frequency of around 2.75 for the case of Froude number of 0.2, around 2.5 for the case of Froude number of 0.37, and around 2.3 for the case of Froude number of 0.51. Generally, the curves show a pre-peak region with a slight ascending tendency together with a post-peak region in which the magnitude of the heave RAO experiences a descending behaviour. The higher the Froude number, the more the slope of the post-peak descending region will be.

It should be mentioned that by changing the value of the wave amplitude from 25 mm to 35 mm, a slight change is shown in the value of nondimensional wave frequency corresponding to the peak value of the heave RAO. In such a case, the peak values of the RAO for the heave motion for the Froude numbers of 0.2, 0.37 and 0.51 are obtained for the nondimensional wave frequencies of around 2.3, 2.3, and 2.2, respectively. This shows that the increase in the wave amplitude from 25 mm to 35 mm does not lead to any significant change in the value of nondimensional frequency corresponding to the peak resonance of the heave RAO, irrespective of the value of the Froude number. The same tendencies as discussed for the case of wave amplitude of 25 mm are still valid herein for the case of wave amplitude of 35 mm.

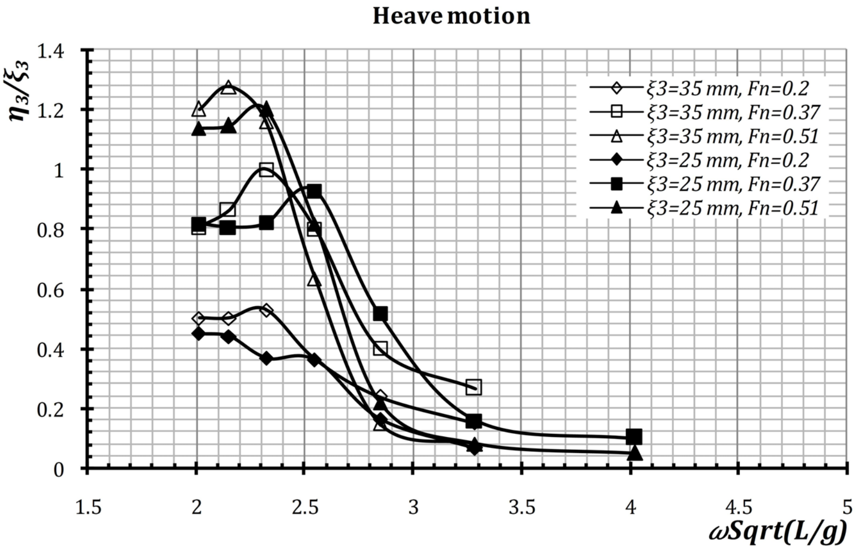


Fig. 11 Heave RAO as a function of nondimensional encountering wave frequency for the trimaran at different Froude numbers for the cases of wave amplitude equal to 25 mm and 35 mm

5.3 Effects of wave length on the pitch motion characteristics

Based on the test results, the curves of pitch RAO versus nondimensional encountering wave length have been drawn for 2 different values of the wave amplitude, as equal to 25 mm and 35 mm, which are respectively shown in the Fig. 12.

Except the case of Froude number of 0.37 in which a clear resonance peak can be identified at the nondimensional wave length of around 1.2 to 1.25, no resonance peak may be clearly detected in the cases of Froude number equal to either 0.2 or 0.51. Diagram of pitch RAO versus nondimensional wave length has almost an ascending tendency in the cases where Froude number is equal to either 0.2 or 0.51.

In addition, it is found that irrespective of the values of Froude number and wave amplitude, pitch RAO does not experience any significant changes when the nondimensional wave length is less than 0.8.

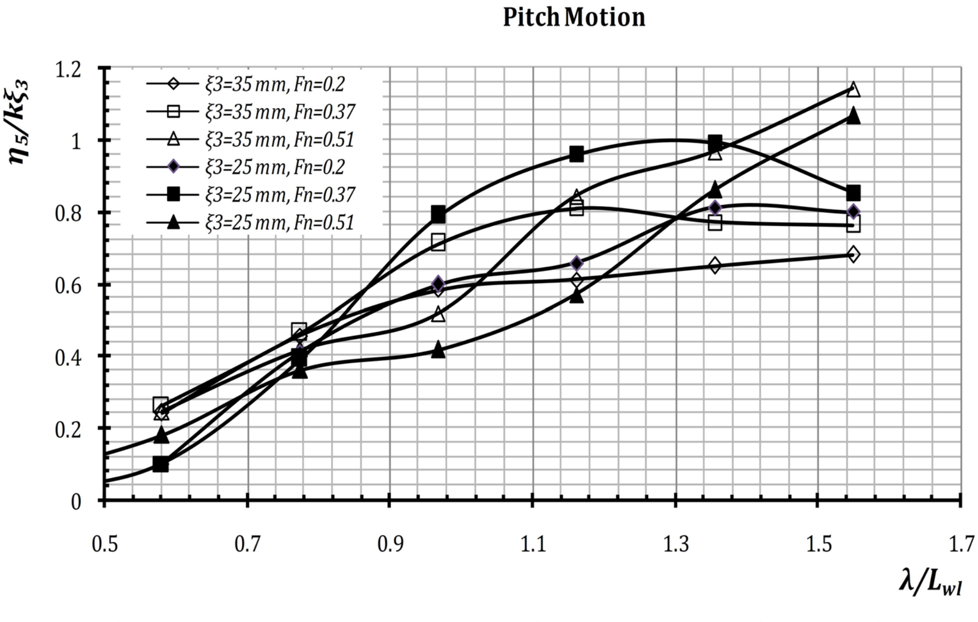


Fig. 12 Pitch RAO as a function of nondimensional encountering wave length for the trimaran at different Froude numbers for the cases of wave amplitude equal to 25 mm and 35 mm

5.4 Effects of wave frequency on the pitch motion characteristics

Figure 13 shows the relationship between the pitch RAO and nondimensional encountering wave frequency for two cases of wave amplitude to be equal to either 25 mm or 35 mm, respectively.

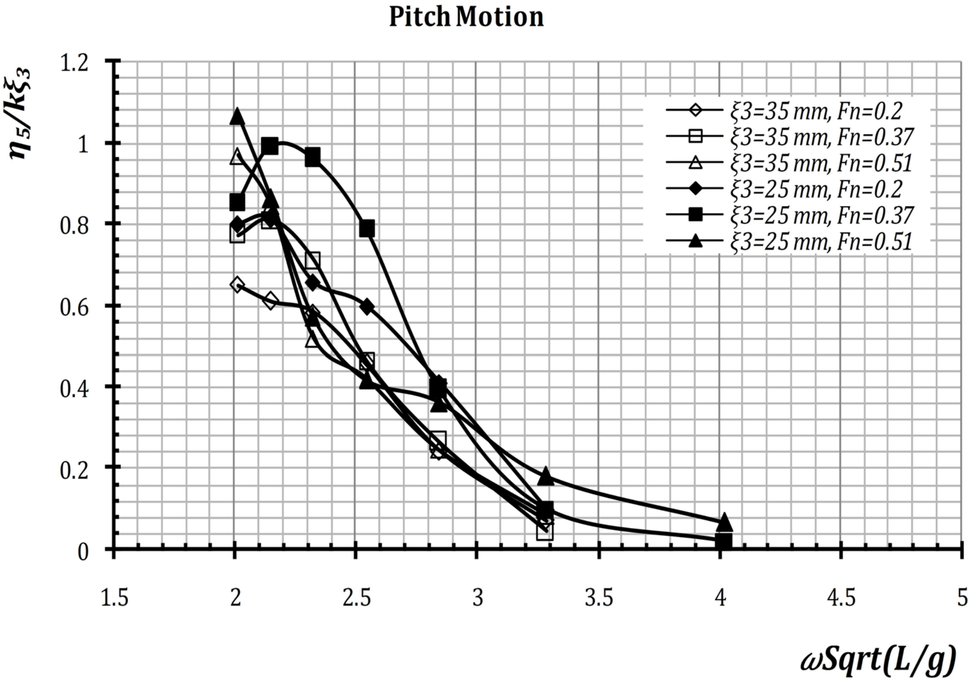


Fig. 13 Pitch RAO as a function of nondimensional encountering wave frequency for the trimaran at different Froude numbers for the cases of wave amplitude equal to 25 mm and 35 mm

Again, except for the case of the Froude number of 0.37 in which a clear resonance peak can be identified at the nondimensional wave frequencies of 2.2 to 2.3, no resonance peak may be clearly detected in the cases of Froude number equal to either 0.2 or 0.51. The diagram of the pitch RAO versus the nondimensional wave frequency has almost a descending tendency in the cases where the Froude number is equal to either 0.2 or 0.51.

In addition, it is found that irrespective of the value of the Froude number, the pitch RAO does not experience any significant changes when the nondimensional wave frequency is more than 2.8 for the case of wave amplitude of 25 mm, Fig. 13. Based on the results presented in Fig. 13, such a threshold applies to the value of 2.5 for the nondimensional wave frequency, when the wave amplitude is equal to 35 mm.

6. CONCLUSIONS

A trimaran model with a length-to-beam ratio of 12.96 is used to experimentally investigate its heave and pitch motions. Sinkage effects are neglected in the experiments. Neither significant changes nor any flare appeared in the body line above the waterplane.

It was found that for lower Froude numbers, the interval between variations in the magnitudes of the RAOs of heave or pitch motions as a result of the change in the wave length, wave frequency, and wave amplitude is not so wide. Such an interval gets wider as the

Froude number becomes higher. Other features of the heave and pitch motions of the trimaran model under consideration are as follows:

The heave RAO has a resonance peak when the nondimensional wave length is around 1.0. Increasing the Froude number leads to rapidly descending post-resonance-peak regions of the heave RAO-nondimensional wave frequency diagrams. Sensitivity of the pitch RAO to the changes in the values of Froude number and wave amplitude is not so great when the nondimensional wave length is less than 0.8. Also, for the values greater than 2.5 to 2.8 of the nondimensional wave frequency, the pitch RAO does not experience any significant changes as a result of variations in the Froude number or wave amplitude.

REFERENCES

[1] Cook, S.M., Couser, P., Klaka, K.: *Investigation into wave loads and catamarans*. Proceedings of the International Conference on Hydrodynamics of High Speed Craft, 24-25 November, London (UK) (1999).

[2] Guedes Soares, C., Fonseca, N., Santos, P. and Marón, A.: *Model tests of the motions of a catamaran hull in waves*. Proceedings of the International Conference on Hydrodynamics of High Speed Craft, 24-25 November, London (UK) (1999).

[3] Mcgoldrick, J.: *Theoretical and experimental study of motion characteristics of catamaran hull forms*. Undergraduate Thesis, Australian Maritime College, Launceston, Tasmania (Australia) (2002).

[4] FormSys, http://www.formsys.com/maxsurf/msproducts/seakeeper (2003).

[5] Fang, C.C., Chan, H.S.: *Investigation of seakeeping characteristics of high-speed catamarans in waves*. Journal of Marine Science and Technology 12(1):7-15 (2004).

[6] Bruzzone, D., Grasso, A., Zotti, I.: *Nonlinear seakeeping analysis of catamarans with a central bulb*. Proceedings of the 6th International Conference on High-Performance Marine Vehicles (HIPER'08), 18-19 September, Naples (Italy) (2008).

[7] Broglia, R., Bouscasse, B., Jacob, B., Olivieri, A., Zaghi, S. and Stern, F.: *Calm water and seakeeping investigation for a fast catamaran*. Proceedings of the 11th International Conference on Fast Sea Transportation (FAST 2011), 26-29 September, Honolulu, Hawaii (USA) (2011).

[8] Begovic, E., Bertorello, C., Bruzzone, D., Cassella, P., Zotti, I. *High speed trimarans-validation of numerical results by geosim tests*. Proceedings of the 6th International Conference on Fast Sea Transportation (FAST 2001), 4-6 September, Southampton (UK) (2001).

[9] Kurultay, A.A.: *Sensitivity analysis of the seakeeping behavior of trimaran ships*. MSc Thesis, Naval Postgraduate School, Monterey, California (USA) (2003).

[10] Pastoor, W., Van 't Veer, R., Harmsen E.: *Seakeeping behaviour of a frigate-type trimaran*. Proceedings of the International Conference on the Design and Operation of Trimaran Ships, Royal Institute of Naval Architects (RINA), 29–30 April, London(UK) (2004).

[11] Begovic, E., Bove, A., Bruzzone, D., Caldarella, S., Cassella, P., Ferrando, M., Tincani, E., Zotti, I.: *Co-operative investigation into resistance of different trimaran hull forms and configurations*. Australian Journal of Mechanical Engineering 3(2):175-182 (2006).

[12] Hebblewhite, K., Sahoo, P.K., Doctors, L.J.: *A case study: theoretical and experimental analysis of motion characteristics of a trimaran hull form*. Ships and Offshore Structures 2(2):149-156 (2007).

[13] Ogawa, Y.: *A study on the prediction method of wave loads of a multi-hull ship taking account of the side hull arrangement*. Proceedings of the 6th International Conference on High-Performance Marine Vehicles (HIPER'08), 18-19 September, Naples (Italy) (2008).

[14] Mynard, T., Sahoo, P.K., Mikkelsen, J., McGreer, D.: *Numerical and experimental study of wave resistance for trimaran hull forms*. Proceedings of the 6th International Conference on High-Performance Marine Vehicles (HIPER'08), 18-19 September, Naples (Italy) (2008).

[15] Mizine, I., Karafiath, G., Queutey, P., Visonneau, M.: *Interference phenomenon in design of trimaran ship*. Proceedings of the 10th International Conference on Fast Sea Transportation (FAST 2009), 5-8 October, Athens (Greece) (2009).

[16] Onas, A.S., Datla, R.: *Non-linear roll motions of a frigate-type trimaran*. Proceedings of the 11th International Conference on Fast Sea Transportation (FAST 2011), 26-29 September, Honolulu, Hawaii (USA) (2011).

[17] Begovic, E., Bertorello, C., Caldarella, S., Cassella, P. *Pentamaran hull for medium size fast ferries*. Proceedings of the 6th International Conference on Hydrodynamics (ICHD 2004), 24-26 November, Perth (Australia) (2004).

[18] http://www.ulstein.com/kunder/ulstein/cms66.nsf/doc/3A6662B6DEF379B3C12576C70031E17D

[19] http://www.marineinsight.com/marine/marine-news/headline/x-bow-hull-design-vs-conventional-hull-design/

[20] Nordås, D.E. *Optimization of bow shape of large slow ship*. Master Thesis, Norwegian University of Science and Technology, Trondheim (Norway) (2012).

[21] Lloyd, A.R.J.M. *Seakeeping: Ship Behaviour in Rough Weather*. Ellis Horwood (1989).

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