An Experimental Research on Nonlinear Roll Hydrodynamic Characteristics of a Composite Trimaran Using ε-SVR

Haitong Xu, Songlin Yang, Qingwei Ma, Baoming Wang, Tianyu Ma and Yuyang Zong

Abstract**—**The rolling motion behaviour of a composite trimaran was studied in the Jiangsu University of Science and Technology Ship hydrodynamic Centre. Series of the free roll decay tests were carried out in the seakeeping tank. The mathematical model of rolling motion mode is established considering both linear and nonlinear ship motion. The overall seakeeping behaviour of the vessel is discussed and particular attention is paid to the roll motion. The results of time-domain nonlinear hydrodynamic identification using ε-Support Vector Regression are validated against the model tests. The error of ε-Support Vector Regression is discussed and the relative error is less than 3%. The results suggest that the ε-Support Vector Regression is a reliable method for identification of the roll motion owning to its inherent benefits. Parametric roll is discussed and test results are presented. The nonlinear effect on the roll motions of the draft, spacing and attitude of side hulls is evaluated. The paper ends with a discussion on configurations of side hull for composite trimaran vessels. This paper can provide technical support in the optimization design of composite trimaran and the research of composite multi-hull ship.

Keywords**—**Composite trimaran, Nonlinear roll hydrodynamic characteristics, Model test, System identification, ε-Support Vector Regression .

I. INTRODUCTION

IN the past 20 years a significant amount of research and development has been devoted to the application of the trimaran concept for both navy and commercial purposes and this has been reported in numerous publications. The trimaran configuration offers many hydrodynamic and layout advantages for ship types that require a relatively high top speed, excellent stability and seakeeping, low loss in waves, a large deck area. The trimaran looks similar to a conventional monohull, but the side-hulls are usually very small, are narrow and support 10% of the total displacement. However these side-hulls can have a significant effect on the dynamic behavior of the vessel and thus the seakeeping performance. Due to the trimaran configuration and the interference of waves created by hulls, It is very complicated to calculate the roll damping theoretically. So model test is the main tool for investigating composite trimaran.

Early research work into trimarns started at UCL in 1990 inspired by Nigel Irens' idea for a small trimaran fast ferry [1]. Lawrence J. Doctors and Robert J. Scrace [2] presented a research of the hydrodynamic interactions of trimarn during rolling motion, the investigation has demonstrated that the traditional strip theory will predict the heave and pitch, but the roll motion is overpredicted by the theory. T J. Granfton and J Zhang [3] studied the appendages potentially providing increases in roll damping in free decay model experiments. The studies into these devices show that significantly more roll damping can be achieved.

The roll motion of a trimaran ship composed of three wigley hulls in beamwave has been studied on an experimental basis by Alberto Francescutto [4]. He established a mathematical model, taking into account the roll motion of main hull and the heave motion of the outriggers, which compared with the results of the experimental tests.

The seakeeping behavior of a frigate-type trimarn was studied by W. Pastoor, R van't Veer and E. Harmsen [5]. The overall seakeeping behavior of the vessel is discussed and particular attention is paid to the roll motion. The nonlinear effect on the roll motions of the intermittent wetting of the side hulls and the size of the hull volume is evaluated. The author also discussed the design load assessments for trimaran vessels.

K. Hebblewhite，P.K.Sahoo and L.J.Doctors [6] found that the position of the trimarn outriggers will have a significant effect on vessel motion characteristics on an experimental basis. Adrian S. Onas and Raju Datla studied non-linear roll motion of a frigate-type trimaran, they found that the 1 DOF nonlinear roll damping models provided accurate predictions of roll motion for the trimaran. The nonlinear roll damping contribution to total roll damping was significant, especially at zero speed due

This work is supported in part by Jiangsu Science and Technology University's "A Project Funded by "Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD)"

H.T. Xu is with the School of Naval Architecture and Ocean Engineering, Jiangsu University of Science and Technology, Jiangsu, Zhenjaing, China (corresponding author to provide phone: 86-511-84446630; fax: 86-511-84446630; e-mail: xht325@ 163.com).

S.L. Yang is with the School of Naval Architecture and Ocean Engineering, Jiangsu University of Science and Technology, Jiangsu, Zhenjiang, China (e-mail: ysl560516@vip.163.com).

Q.W. Ma is with the School of Engineering and Mathematical Sciences, City University, London, UK.(q.ma@city.ac.uk)

B.M. Wang, T.Y. Ma and Y.Y. Zong are with the School of Naval Architecture and Ocean Engineering, Jiangsu University of Science and Technology, Jiangsu, Zhenjiang, China.

to viscous effects such as friction and vortex shedding.

The literature [7] presented neural network for modeling of underwater vehicle dynamics. Researches show that neural model is very good adjustment to the objects taking as coefficient the square average error and this method can be used to the time varying identification. From the literature[8] the Neural Network (NN) controller for a container ship roll stabilizer system performs significantly better than the passive one and the simulation results showed that the performances of Neural Network (NN) controllers are excellent. The literature [9] presented a solution method based on a fully viscous non-linear flow solver used to evaluate the two dimensional hydrodynamic coefficients of damping and added mass appearing in the generalized linear equations of motion of a ship in a seaway and the results agree very well with experimental measurements for these two quite different section shapes, validating the satisfactory accuracy of the proposed method. From the literature [10], Results obtained by a fully viscous method for the evaluation of hydrodynamic added mass and damping of oscillating bodies were presented, in general showing good correlation with the available experimental results.

System identification method [11] has been used to identify the hydrodynamic coefficients and their correlation coefficient of ship movement and establish its mathematical model in ship model test [12]-[18]. Feng Zhu and Songlin Yang [19] established the mathematical model of system identification of composite trimaran pitching motion model based on the genetic optimization algorithm. The results of forecast can well match with the test results and validated the feasibility of this set of identification method.

The literature [20] found that the SVM model was able to provide more reliable estimations compared to LLR, CGNN and BFGSNN models. Luo and Zou[21] applied LS-SVM ,while Zhang and Zou [22] adopted ε-SVR, to identify Abkowitz model for Mariner class surface ship and gained satisfactory results. The purpose of these works is to determine the hydrodynamic coefficients of a Mariner-class vessel, although the identification of the mathematical model is made with data obtained from simulation and then tested only in simulation. These works do not deal with real data. Furthermore, in their studies, linear kernel function was selected for off-line parametric identification.

In this study the roll motion mode of a composite trimaran is investigated as a function of side hull attitude, transverse spacing and total displacement. The free roll decay experiments were conducted at the Jiangsu University of Science and Technology Ship hydrodynamic Centre. The author makes an effort to apply ε-SVR in identification modeling of a composite trimarans' nonlinear roll. SVM with linear kernel function is applied for regression of the nonlinear functions in the dynamic model. From the identification data, we get figures of hydrodynamic coefficients and their correlation coefficients changing with the draft molded depth (T/D), the transverse spacing length (b/L) and the inclination angle of the outriggers. The experiments and the method in this paper will serve as benchmarks for further study and design validation of the trimarans' research.

II. Principal Dimension of Composite Trimaran Model

The trimaran model in the experiments was converted from a Navy frigate. Its principal dimensions were shown in Table 1. The experiments ignore the effect of the longitudinal distance of side hull, so side hull was arranged from the cross section of the main hull (L=950mm).

Table 1 the principal dimensions of the trimaran

Main dimensions	Symbol	Value
Design waterline length of main hull[m]	LW_l	2.7
Main hull breadth[m]	B	0.19
Main hull depth[m]	D	0.187
Design draft of main body[m]	T	0.085
Side hull length[m]	L_1	0.8
Side hull breath[m]	B_1	0.03
Side hull depth[m]	D_1	0.12
Design draft of side hull[m]	T_1	0.050
Design total displacement[m]	Δ	22.5

The composite trimaran model with hydrofoils equipped on the main hull and side hulls was shown in Fig.1. Hydrofoil installed on the ship model, was made of Q235 steel. The cross section of hydrofoil is bow-type profile. The hydrofoil can provide 15% of the total displacement under maximum speed in theory. The principal dimension of hydrofoil was shown in Table 2.

Fig. 1 the composite trimaran model

Table 2 the principal dimensions of hydrofoil

	Span	Chord	Max. thickness	Camber	Aspect ratio
Main hull	220mm	50 mm	5 mm	2.5 mm	4.4
Side hull	154 mm	35 mm	4 mm	2 mm	4.4

MTi-G (Fig.2) is a miniature inertial measurement system integrated GPS signal. It output attitude and heading information through the processing of the internal microprocessor and provide accurate position and velocity information through real-time Kalman filter.

Fig.2 Mti-G Micro AHRS System

III. IDENTIFICATION METHOD AND MATHE-MATICAL MODEL OF THE COMPOSITE TRIMARAN

Owing to the least square method have some inherent drawbacks, such as overfitting, multiple local minima problem, seriously depending on the initial value of parameters, etc. The theoretical accuracy depends on the number of the data. These problems can be avoided using SVM since it is not based on the empirical error; rather it is based on the structural risk minimization. So SVM provides a larger generalization performance. Vanik-Chervonenkis (VC) theory is the basic idea behind SVM which defines a measure of the capacity of a learning machine [23]-[25]. SVR has the ability to simultaneously minimize the estimation error in the training data (the empirical risk) and the model complexity (the structural risk). Moreover, SVR can be designed to deal with sparse data, where we have many variables but few data. Furthermore the solution of SVR is globally optimal.

The use of ε-SVR is very similar to tis use for classification. Following the notation and definitions in [26]-[27], consider a model in the primal weight space:

$$y(x) = \omega^T \varphi(x) + b \qquad (1)$$

Where: x is the input data, y is output data, b is bias term,ω is a matrix of weights and $\varphi(:)$ is the mapping to a high-dimensional space.

For the ε-Support Vector Regression, the standard form of Support Vector Regression is

$$\min_{w,b,\varepsilon,\varepsilon^*} F(\omega,\varepsilon) = \tfrac{1}{2}\omega^T\omega + C\sum_{i=1}^{l}\varepsilon_i + \sum_{i=1}^{l}\varepsilon_i^* \qquad (2)$$

Subject to:

$$\omega^T\varphi(x_i) + b - y_i \le \epsilon + \varepsilon_i$$
$$y_i - \omega^T\varphi(x_i) - b \le \epsilon + \varepsilon_i$$
$$\varepsilon_i, \varepsilon^*{}_i \ge 0, i = 1\cdots l \qquad (3)$$

The above primal problem can't be solved when ω becomes infinite dimensional. Thus, the Lagrangian must be computed and the dual is :

$$\min_{\alpha,\alpha^*} \frac{1}{2}(\alpha-\alpha^*)^T Q(\alpha-\alpha^*) + \epsilon\sum_{i=1}^{l}(\alpha_i + \alpha_i{}^*) + \sum_{i=1}^{l} y_i(\alpha_i - \alpha_i{}^*) \qquad (4)$$

Subject to:

$$\sum_{i=1}^{l}(\alpha_i - \alpha_i{}^*) = 0, 0 \le \alpha_i, \alpha_i{}^* \le C, i = 1,\cdots,l \qquad (5)$$

In order to estimation parameters, the present article chooses the linear kernel function $K(x_i, x) = (x_i, x)$ to identify hydrodynamic coefficients.

Wave making is a major energy dissipation mechanism for ship motions with the exception of roll. Viscous effects due to the presence of a boundary layer and vortex shedding induced by sharp edges, vortex shedding and hydrofoil can have a significant contribution to total roll damping. According to the dynamic balance of principle, the total moment of the x-ax is zero at any moment acting on the ship model, so we can get the equation:

$$M(\ddot\varphi) + M(\dot\varphi) + M(\varphi) = 0 \qquad (6)$$

According to the characteristics of movement and force, we established the following roll motion equation of the composite trimaran:

$$I_X\ddot\varphi + 2N_\varphi\dot\varphi + W|\dot\varphi|\dot\varphi + x\dot\varphi^3 + C*\sin(\varphi) = 0 \qquad (7)$$

$$\ddot\varphi + 2\frac{N_\varphi}{I_X}\dot\varphi + \frac{W}{I_X}|\dot\varphi|\dot\varphi + \frac{x}{I_X}\dot\varphi^3 + C*\sin(\varphi)/I_X = 0 \qquad (8)$$

Where: I_X = virtual added mass moment of inertia; N_θ = linear roll damping; W = square roll damping; x = cubic roll damping; C= roll restoring; $\ddot\varphi, \dot\varphi, \varphi$= roll acceleration, roll velocity and roll amplitude, respectively.

According to Eqs.(8), the author choose $\{\dot\varphi_k, |\dot\varphi_k|\dot\varphi_k, \dot\varphi_k{}^3, \sin(\varphi_k)\}$ as input datas and $\{\varphi_{k+1}\}$ as output datas. The insensitivity factor ε=0 and the penalty factor $C=10^6$ are chosen. The hydrodynamic coefficients ($N_\varphi/I_{x,} W/I_{x,}, x/I_{x,}, C/I_{x,}$) are parameters to be identified.

IV. FREE ROLL DECAY EXPERIMENT OF THE COMPOSITE TRIMARAN

The experiments were carried out in the tank of Jiangsu University of Science and Technology. The tank is 38m long, 15m wide, 1.2m deep. Fig.3 is the composite trimaran during free roll decay test. During experiments , the humidity of the laboratory is about 70% and the water temperature is about 20° C.

Fig.3 Free damping rolling test

In order to minimize wave reflection from the tank walls, the composite Trimaran model is aligned across the tank in the still water. The experiments were carried out by changing the transverse spacing of side hull (285mm, 335mm, 385mm, 422mm, 460mm), the draft (71mm, 77mm, 83mm, 87mm, 91mm). In order to study the rolling motion mode comprehensively, we select initial roll angle from 4°-15°. The transverse spacing and the attitude of side hull have a significant effect on the rolling motion. So anther experiments were carried out by changing the transverse spacing of the outriggers (285mm, 335mm, 385mm, 422mm, 460mm) and the angle of side hull(±5°, ±7° ,+10°). The angle is the positive when the side hull tilt inward. Fig.4 is the wave-making around the composite trimaran in the rolling test.

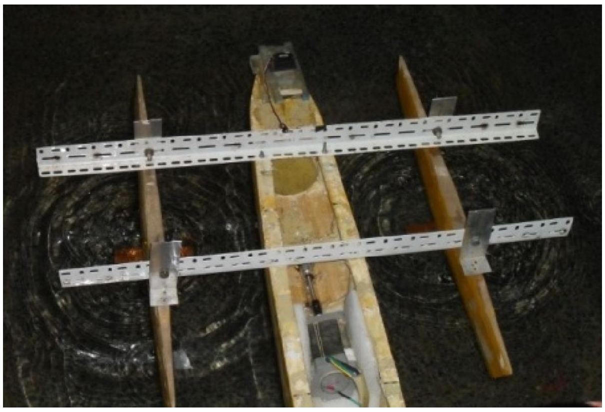
Fig.4 The wave during the rollin test

V. Analysis of the Experimental Data

Based on the above mathematical model and optimization methods, the author programmed identification software. In order to verify the reliable of the identification software, we identified the 15° free decay with the draft is 83 mm and the transverse spacing is 422 mm. So we got roll motion equation:

$$\ddot{\varphi} + 2 * 0.287\dot{\varphi} + 8.698|\dot{\varphi}|\dot{\varphi} - 5.702\,\dot{\varphi}^3 + 52.393 * \sin(\varphi) = 0$$

According the roll motion equation, we choose the initial roll angle of 15° to verify the recognition results. Fig.5 is the identification curve. From the Fig.5, the identification and experimental curves are in good agreement. Choosing identification and experimental values in a periods, we got the relative error in Table 3. As shown in Table 3 below, the relative error was small and basically in less than 3%. So the identification software is reliable.

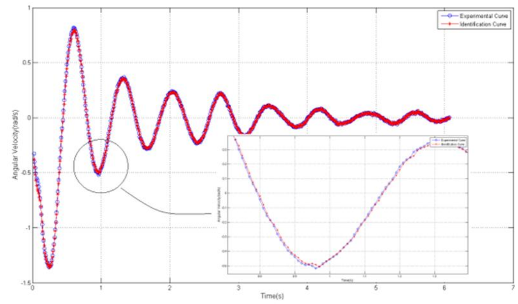

Fig.5 15° free roll decay angular velocity curve

Table 3. The error analysis of angle velocity of identified result

Time(s)	Test values(rad/s)	Identify value(rad/s)	Absolute error	Relative error(%)	Time(s)	Test values(rad/s)	Identify value(rad/s)	Absolute error	Relative error(%)
0.110	-0.730	-0.750	0.020	2.786	0.510	0.538	0.527	0.011	2.046
0.120	-0.809	-0.807	0.002	0.201	0.520	0.592	0.575	0.017	2.888
0.130	-0.880	-0.879	0.001	0.083	0.530	0.651	0.633	0.018	2.798
0.140	-0.969	-0.944	0.026	2.662	0.540	0.686	0.665	0.020	2.928
0.150	-1.053	-1.026	0.027	2.548	0.550	0.711	0.695	0.016	2.312
0.160	-1.116	-1.104	0.012	1.088	0.560	0.751	0.716	0.035	4.618
0.170	-1.187	-1.162	0.025	2.146	0.570	0.771	0.750	0.021	2.788
0.180	-1.224	-1.228	0.004	0.288	0.580	0.788	0.765	0.023	2.907
0.190	-1.251	-1.260	0.009	0.700	0.590	0.810	0.788	0.022	2.739
0.200	-1.283	-1.282	0.001	0.112	0.600	0.817	0.794	0.023	2.842
0.210	-1.315	-1.308	0.006	0.462	0.610	0.813	0.797	0.016	1.972
0.220	-1.319	-1.335	0.016	1.193	0.620	0.802	0.789	0.013	1.587
0.230	-1.346	-1.333	0.013	0.973	0.630	0.782	0.774	0.009	1.091
0.240	-1.358	-1.354	0.004	0.282	0.640	0.754	0.751	0.003	0.449
0.250	-1.348	-1.360	0.012	0.854	0.650	0.731	0.720	0.012	1.608
0.260	-1.351	-1.342	0.008	0.620	0.660	0.689	0.694	0.005	0.717

The literature [28] presented that the additional mass as well as additional moment of the trimaran can be influenced by interaction among three bodies, but not quite obviously, and the influence will decrease quickly while the distance between bodies increases. So the roll hydrodynamic coefficients (N_{φ}/I_{x}, W/I_{x}, x/I_{x}, C/I_{x}) reflect the law of the damping and the roll restoring in some extent.

The author makes figures of the roll hydrodynamic coefficients and their correlation coefficient (N_{φ}/I_{x}, W/I_{x}, x/I_{x}, C/I_{x}) using identification data.

A. The effect of the Transverse Spacing

Fig.6 through 8 is the curve of the roll hydrodynamic coefficients (N_{φ}/I_{x}) changing with the b/L. According to the Fig.6 we can see that the composite trimaran's linear roll damping is influenced by the transverse spacing length (b/L) in the case of draft is 71mm. Linear roll damping has the same trend in most cases and decreases with b/L. when the initial roll angle is 8°and 12°reaches its trough value at b/L≈ 2 and then increase with the transverse spacing. When the draft is 83mm, showed in the Fig.7, linear roll damping presents the different trend with the case T=71mm. From the Fig.7, the linear roll damping increase rapidly with the transverse spacing and reach its peak value at b/L≈ 2. When the initial roll angle is small (6°and 8°), the linear roll damping has a dramatic changes. When the draft is 91mm, the linear roll damping has the same trend in most cases. It firstly decreases rapidly with the transverse spacing and reaches its trough value at the b/L≈ 2.1, then increase rapidly.

From the Fig. 6 through 8, we can get the conclusion that the linear roll damping is influenced by the transverse spacing and the draft. When the draft is 81mm, the linear roll damping varies between -0.2-3.5 in all cases; when the draft is 83mm, it varies between -2-11 in all cases; when the draft is 91mm, it varies between -0.2-2.5 in all the cases. So the draught affects the linear roll damping's degree of influence by the transverse spacing. During the experiment, we can find that when the draft is 83mm, the interference between the main hull and outriggers is most serious.

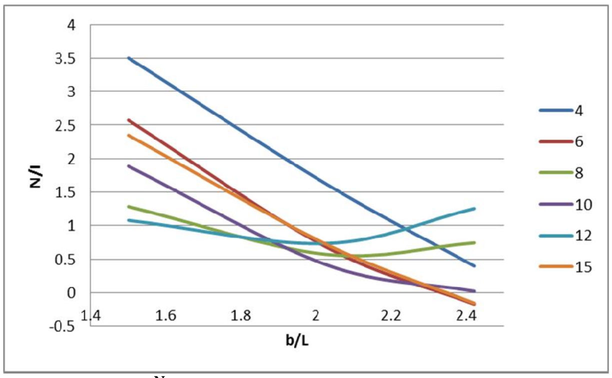

Fig. 6 Figure of $\frac{N_{\varphi}}{I_{x}}$ changes with the transverse spacing length (b/L) in the case T=71mm

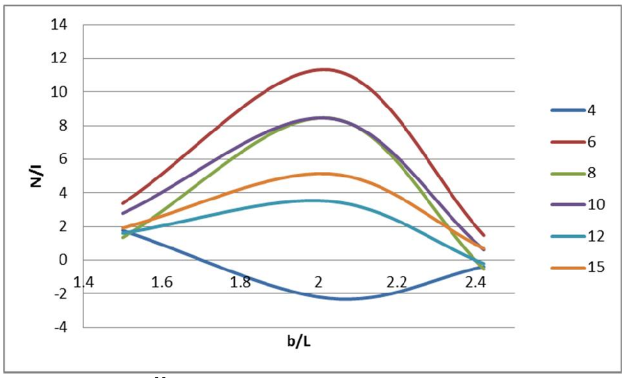

Fig. 7 Figure of $\frac{N_{\varphi}}{I_{x}}$ changes with the transverse spacing length (b/L) in the case T=83mm

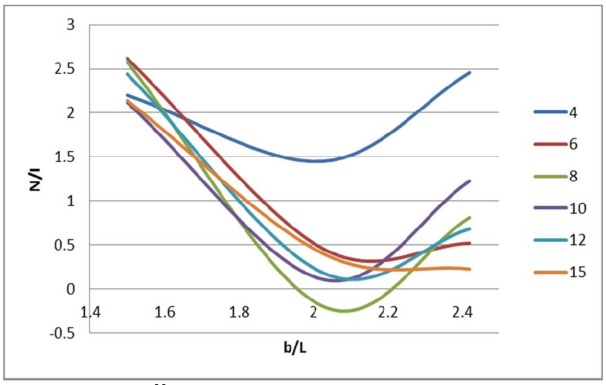

Fig. 8 Figure of $\frac{N_{\varphi}}{I_{x}}$ changes with the transverse spacing length (b/L) in the case T=91mm

Fig.9 through11 display the curve of the roll hydrodynamic coefficient (W/I_{X}) changing with the transverse spacing length b/L. According to the Fig.6 we can see that the composite trimaran's square roll damping is influenced by the transverse spacing length (b/L) in the case of draft is 71mm. the square roll damping increase with the transverse spacing length. From the Fig.10, The square roll damping decreases firstly with the transverse spacing and reaches its trough value at the about b/L≈2, then increase rapidly. The square roll damping has the same trend in the most cases except the case of the initial roll angle is 4°. Fig.11 presents the square roll damping for all cases, when the initial roll angle is 4°and 8°, the square roll damping have the same trend, though their values are different in the different ranges, the square roll damping increase rapidly and reaches its peak value at about b/L ≈ 2 , then decrease rapidly. When the initial roll angle is greater than 10°, the square roll damping increases rapidly before the b/L is 2 and then remains stable.

From Fig.9 through 11, there is a significant result, suggesting that the square roll damping have the different trend when the draft gets the different values. In the most cases, the square roll damping increase with the transverse spacing. So we can get the conclusion that the square roll damping is influenced by the the transverse spacing and the draft.

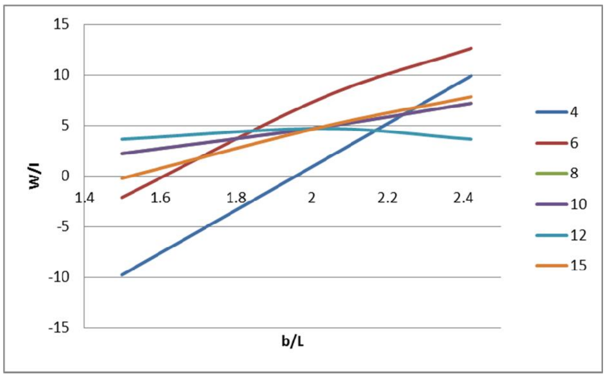

Fig. 9 Figure of $\frac{W}{I_x}$ changes with the transverse spacing length (b/L) in the case T=71mm

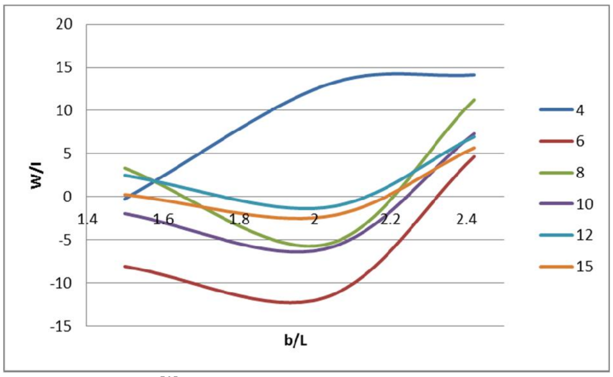

Fig.10 Figure of $\frac{W}{I_x}$ changes with the transverse spacing length (b/L) in the case T=83mm

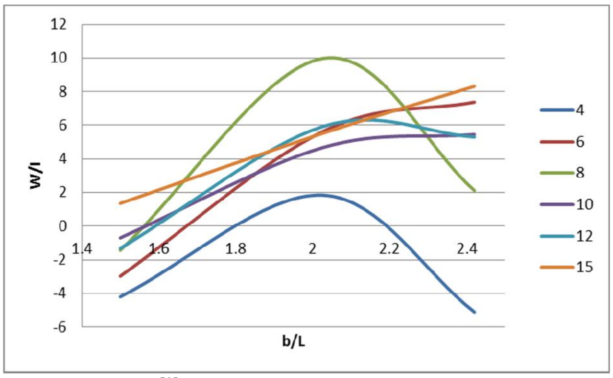

Fig.11 Figure of $\frac{W}{I_x}$ changes with the transverse spacing length (b/L) in the case T=91mm

Fig.12 through14 display the curve of the cubic roll damping changing with b/L; Fig.12 show that the composite trimaran' the cubic roll damping is influenced by the transverse spacing of side hull when the draft is 71mm. The cubic roll damping has the different trends when the initial roll angle is different. As shown in the Fig.12, the cubic roll damping decrease with transverse spacing when the initial roll angle is small, such as 4° and 6°. But when the initial roll angle is bigger than 8°, the cubic roll damping has a little change. As the draft increases, the trends of the cubic roll damping have changed. Such as when the draft is 83mm, as shown in the Fig.13, the cubic roll damping has completely different trends when the initial roll angle is 4°and 6°. In other cases, the cubic roll damping changes slightly. When the draft is 91mm, the cubic roll damping has the same trend, though their values are different in the different ranges when the initial angle is small. As shown in the Fig.14, when the initial angle is 4° and 8°, the cubic roll damping decrease slightly and reaches its trough value at about b/L ≈ 2.0, then increase rapidly with the transverse spacing. When the initial angle is big, such as 10°, 12° and15°, the cubic roll damping has a slight change.

From Fig.12 through 14, there is a significant result, suggesting that the cubic roll damping remains almost stable when the initial roll angle is big. The effect of the transverse spacing is small in such cases. But the initial angle is small, the effect of the transverse spacing is obviously and the trend of the cubic roll damping is different when the draft gets the different values.

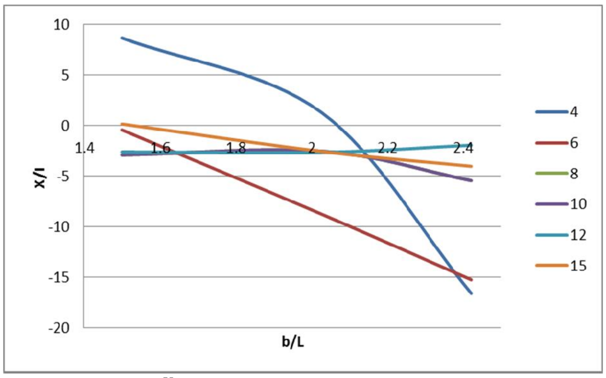

Fig.12 Figure of $\frac{X}{I_x}$ changes with the transverse spacing length (b/L) in the case T=71mm

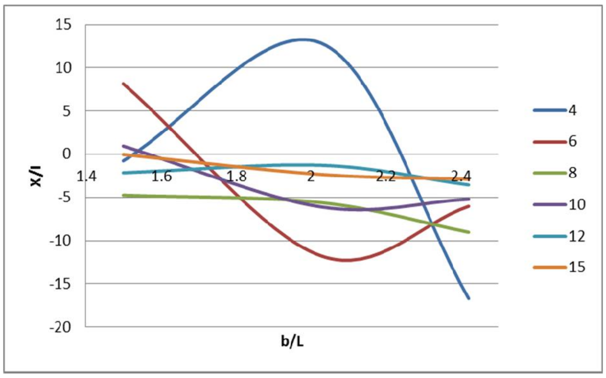

Fig.13 Figure of $\frac{X}{I_x}$ changes with the transverse spacing length (b/L) in the case T=83mm

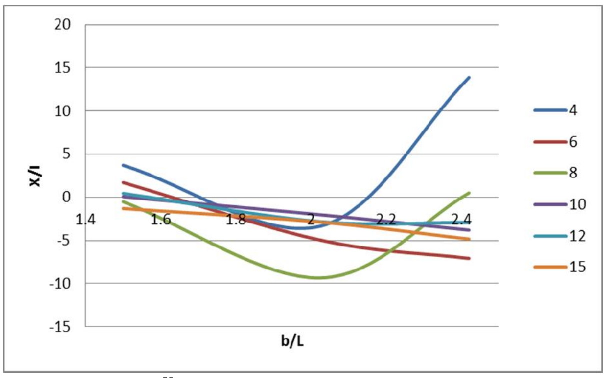

Fig.14 Figure of $\frac{X}{I_x}$ changes with the transverse spacing length (b/L) in the case T=91mm

Fig.15 hrough17 display the curve of the roll restoring changing with the transverse spacing; Fig.15 show that the composite trimaran' roll restoring is influenced by the transverse spacing of side hull. The roll restoring has the same trend in all cases and increase rapidly before b/L≈ 2.0 and then almost remains stable with the transverse spacing. The initial roll angle has a little effect especially when the transverse spacing length is about 2.2. From the Fig.16, the roll restoring has the same trend when the draft is 71mm and 83mm. the roll restoring reach its peak value when the transverse spacing is 2.1. Fig.17 presents the roll restoring change with the transverse spacing when the draft is 91mm. For all cases, the roll restoring increase rapidly in the range of b/L< 2.0 and then almost remains stable with the transverse spacing. When the transverse spacing is 1.5, as shown in the Fig.17, the effect of the initial roll angle is obvious. From the above analysis, so we can get the conclusion that the roll restoring increase with the transverse spacing. The effect of the draft is not obvious.

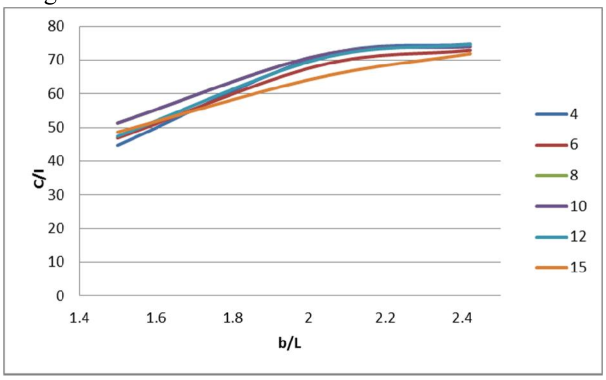

Fig.15 Figure of $\frac{C}{I_x}$ changes with the transverse spacing length (b/L) in the case T=71mm

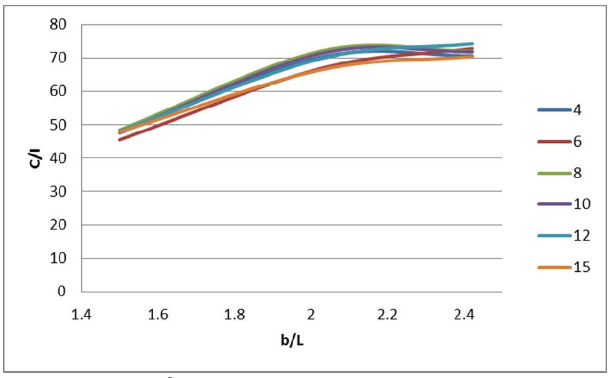

Fig.16 Figure of $\frac{C}{I_x}$ changes with the transverse spacing length (b/L) in the case T=83mm

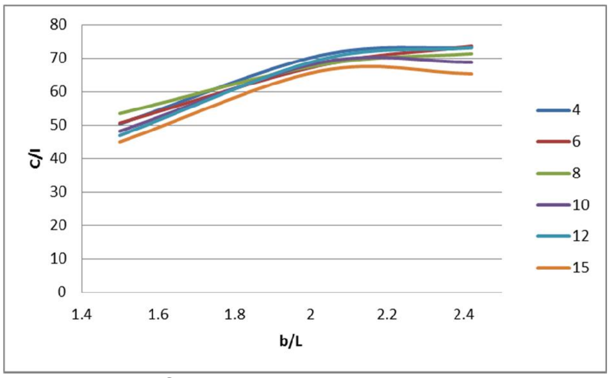

Fig.17 Figure of $\frac{C}{I_x}$ changes with the transverse spacing length (b/L) in the case T=91mm

B. *The effect of the angle of the outriggers*

In order to study the effect of the attitude of the outriggers, the author carried out the roll decay test by changing the transverse spacing of the outriggers (285mm, 335mm, 385mm, 422mm, 460mm) and the angle of side hull(±5°,±7°,+10°). The attitude of the outriggers has an important effect on the performance of the composite trimaran, which had be presented in the literature [29]-[31]. The literature [29] presented a new trimaran model with slant side hulls, with which several resistance experiments have been conducted in a towing tank. The experiments first measured the model resistance of the trimaran at different slant angles and with different loads. The results show that selecting the appropriate slant angle of side hulls would reduce the sailing resistance of trimaran. In the literature [30], the flow field around a trimaran is simulated; wave contour shows that CFD can clearly reflect the interaction among the component hulls of trimaran. Calculated results have some reliability in simulating the viscous flow field around trimaran. The literature [31] found that the resistance of the slant-side hull trimaran is a little bigger than that of the vertical side hull trimaran when the speed is low, but, it is contrary when the speed is high. This shows that the slant-side hull trinlaran is better in high speed. Although the research on the resistance performance of the slant-side hull trimaran had been carried out by some researchers, the research on the roll performance has been rarely reported. So an experimental research on the roll hydrodynamic characteristics of a composite trimaran has been carried out by using ε-SVR.

Fig.18 through21 display the curve of the roll hydrodynamic coefficient (N_{φ}/I_x) changing with the transverse spacing length b/L. Fig.18 show that the composite trimaran' linear roll damping is influenced by the transverse spacing of the outriggers when the angle of outrigger is -10°. The linear roll damping has the same trend in most cases and decrease rapidly before b/L≈ 2.0 and then remains stable. When the initial roll angle is 4°, the linear roll damping presents the different trends. It decreases rapidly in the range of b/L< 2.0 and reaches its trough value, then increases with the transverse spacing. From the Fig.19, the linear roll damping has same trends in most cases when the angle of outrigger is -5°. The linear roll damping decreases rapidly in the range of b/L<2.1, reach its trough value at about b/L≈ 2.1 and then increase with the transverse spacing. But when the initial roll angle is 4°, the linear roll damping presents the opposite trend. It firstly increases, and reaches its peak value at about b/L≈ 2.1, then decreases with the transverse spacing. From the Fig.20, when the angle of the outriggers is 5°, the linear roll damping has the same trend in all cases, though their values are different in the different ranges. The linear roll damping reaches its trough value at about b/L≈ 2.0 respectively. Fig.21 presents the linear roll damping changing with the transverse spacing. From the figure, we can get the conclusion that the linear roll damping decrease with the transverse spacing. But when the initial roll angle is different, the trend in the range of b/L>2.0 is different.

From Fig.12 through 14, there is a significant result, suggesting that the attitude of the outriggers have an important influence on the change of the linear roll damping. In the most cases, the linear roll damping decreases firstly and the reaches its trough value at about b/L≈ 2.0 respectively, then increase rapidly with the transverse spacing. From the figures, we can find that when the angle of the outriggers is bigger, such as$\pm 10°$, the linear roll damping does not have very dramatic changes in the range of b/L> 2.0 in some cases.

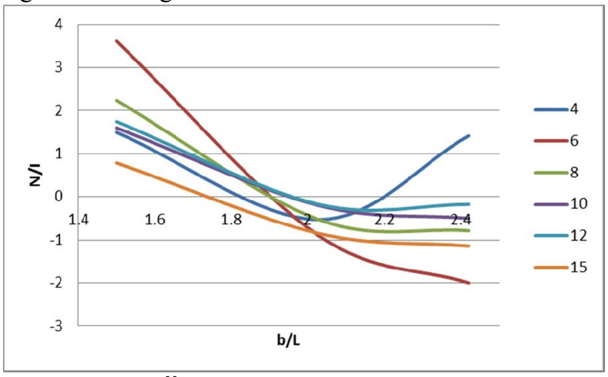

Fig.18 Figure of $\frac{N_\varphi}{I_x}$ changes with b/L in the case the angle of outrigger is -10°

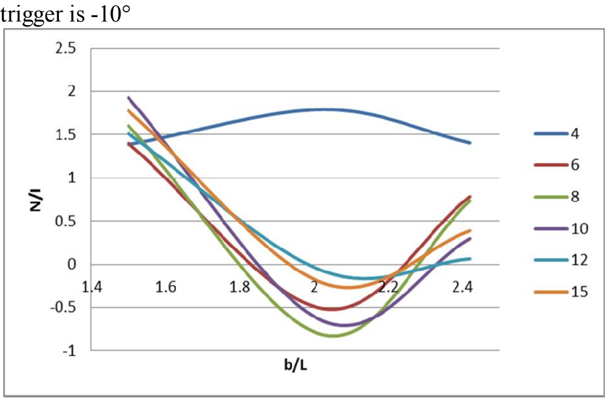

Fig.19 Figure of $\frac{N_\varphi}{I_x}$ changes with b/L in the case the angle of outrigger is -5°

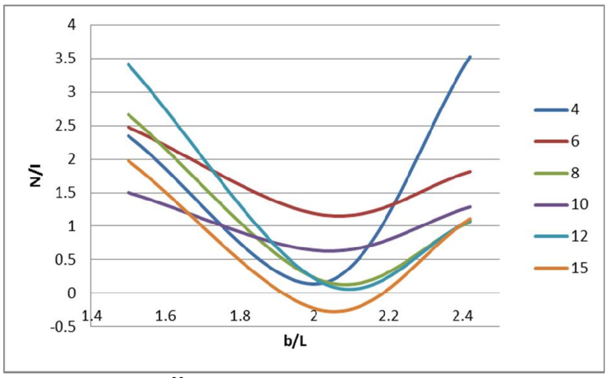

Fig.20 Figure of $\frac{N_\varphi}{I_x}$ changes with b/L in the case the angle of outrigger is 5°

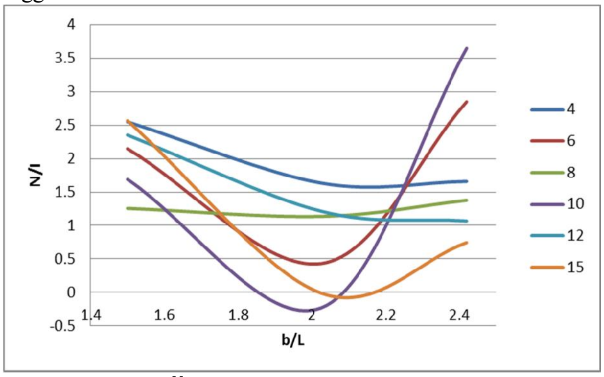

Fig.21 Figure of $\frac{N_\varphi}{I_x}$ changes with b/L in the case the angle of outrigger is 10°

Fig.22 through25 display the curve of the square roll damping changing with b/L when the outriggers tilt an angle. Fig.22 show that the composite trimaran' square roll damping is influenced by the transverse spacing of the outriggers when the angle of the outriggers is -10°. When the initial roll angle is bigger than 6°, the square roll damping has the same trend. The square roll damping increases rapidly and reaches its peak value at about b/L=2.0, then remains stable with the transverse spacing. When the initial roll angle is 4°, it increases rapidly and reaches its peak value at about b/L=2.0, then decreases rapidly with the transverse spacing. When the initial roll angle is 6°, the square roll damping increases along with the transverse spacing. So we can get the conclusion that the initial roll angle has an influence on the trend of the square roll damping. When the initial roll angle is big, the square roll damping has the same trend with the transverse spacing. Fig.23 presents the square roll damping changing with the transverse spacing when the angle of the outriggers is -5°. From the figure, we can find that the square roll damping increase with the transverse spacing and get its peak value at about b/L≈ 2.1 respectively. Then the square roll damping decrease with the transverse spacing. When the angle of the outriggers is 5°, as shown on the Fig.24, the square roll damping increase with the transverse spacing respectively and reach the same value at b/L≈ 2.4. Fig.25 show that the composite trimaran' square roll damping changing with the transverse spacing when the angle of the outriggers is 10°. When the initial roll angle is 4°, 12° and 15°, the square roll damping has the same trend, though their values are different in different ranges. It can be seen from the Fig.25, the square roll damping increase rapidly with the transverse spacing and reach its peak value, then decrease slightly. When the initial roll angle is 6° and 10°, the square roll damping have the same trend. They increase rapidly in the range of b/L< 2.0 and reach the peak values, then decrease rapidly with the transverse spacing.

Form the Fig.22 through25; we can get the conclusion that the square roll damping has been seriously affected by the transverse spacing. In the most cases, the square roll damping reaches its peak value at b/L≈ 2.0. The initial roll angle also has some influence on the trend of the square roll damping.

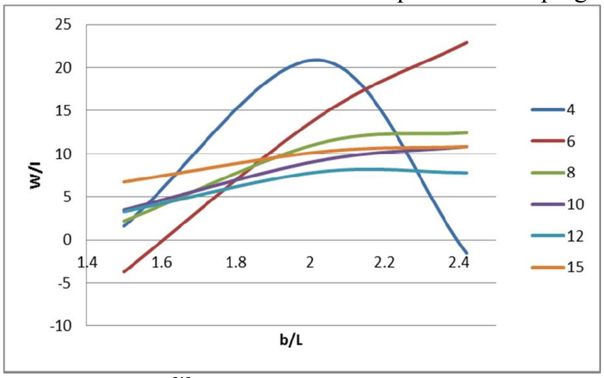

Fig.22 Figure of $\frac{W}{I_x}$ changes with b/L in the case the angle of outrigger is -10°

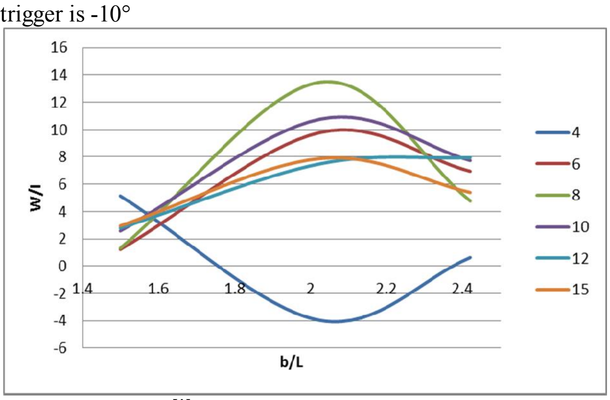

Fig.23 Figure of $\frac{W}{I_x}$ changes with b/L in the case the angle of outrigger is -5°

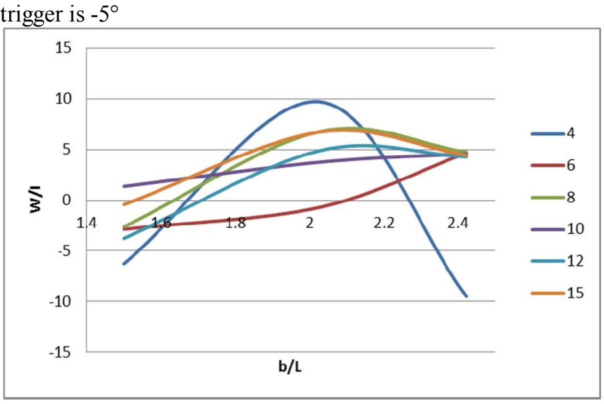

Fig.24 Figure of $\frac{W}{I_x}$ changes with b/L in the case the angle of outrigger is 5°

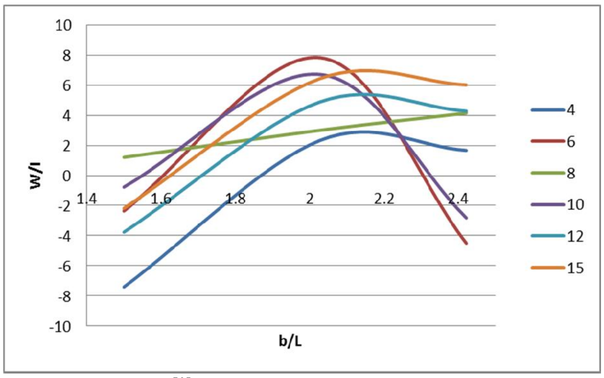

Fig.25 Figure of $\frac{W}{I_x}$ changes with b/L in the case the angle of outrigger is 10°

Fig.26 through29 display the curve of hydrodynamic coefficient (x/I_x) changing with the transverse spacing length b/L when the outriggers tilt an angle. Fig.26 show that the composite trimaran' cubic roll damping is influenced by the transverse spacing of the outriggers when the angle of the angle of the outriggers is -10°. From the figure, we can find the trend of the cubic roll damping of the composite trimaran is different when the initial roll angle is different. As shown on the figure, the cubic roll damping looks unchanged when the initial roll angle is big. When the initial roll angle is small, such as 4°, the cubic roll damping decreases rapidly in the range of b/L< 2.0 and reaches its trough value at about b/L=2.0, then increase rapidly in the range of b/L> 2.0. From the Fig.27, when the angle of the outriggers is -5°, the cubic roll damping decreases in the range of b/L< 2.0 and reaches the trough value at about b/L=2.0, then increase with the transverse spacing. When the initial roll angle is 4°, the cubic roll damping increases rapidly and reaches its peak value at about b/L=2.1. From the Fig.28, when the angle of the outriggers is 5°, the cubic roll damping has the same trend when the initial roll angle is bigger than 6°. When the initial roll angle is 4°, the cubic roll damping decrease rapidly in the range of b/L<2.0 and reaches its trough value, then increase rapidly in the range of b/L>2.0. When the initial roll angle is 10°, as shown on the Fig.29, the cubic roll damping has the same trend when the initial roll angle is 4°, 6° and 10°, though their values are different in different ranges. The cubic roll damping decreases with the transverse spacing and reaches its trough value at about b/L=2.0. But when the initial roll angle is 8°, 12° and 15°, the cubic roll damping has the same trend. The cubic roll damping decreases with the transverse spacing.

From Fig.12 through 14, there is a significant result, suggesting that the cubic roll damping decreases with the transverse spacing. When the angle of the outriggers is small, such as -10°, the cubic roll damping looks unchanged in the all ranges. But when the angle of the outriggers is bigger, the change of the cubic roll damping is more seriously. The initial roll angle also has an important effect on the trend of the cubic roll damping.

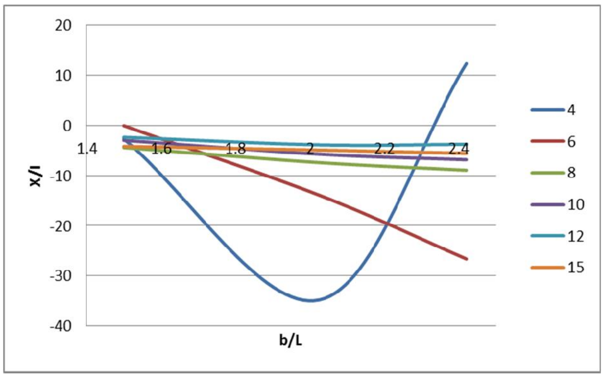

Fig.26 Figure of $\frac{x}{I_x}$ changes with b/L in the case the angle of outrigger is -10°

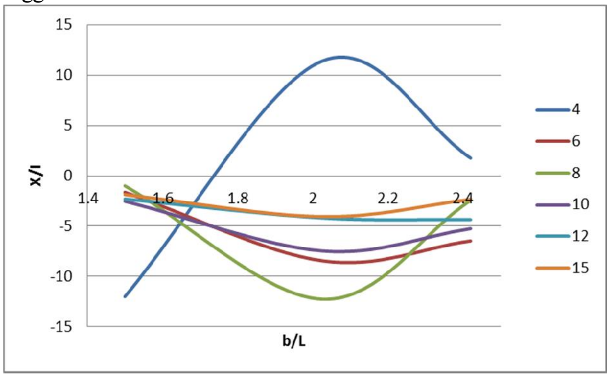

Fig.27 Figure of $\frac{x}{I_x}$ changes with b/L in the case the angle of outrigger is -5°

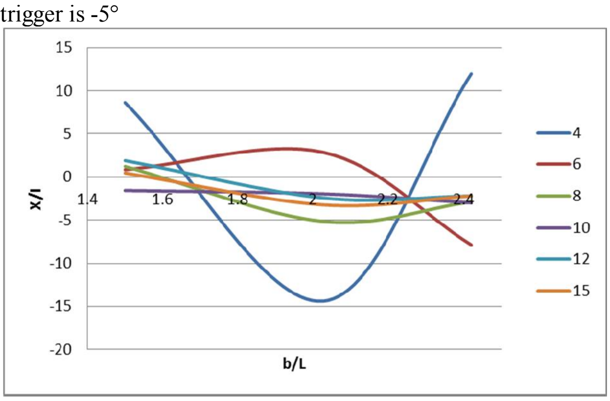

Fig.28 Figure of $\frac{x}{I_x}$ changes with b/L in the case the angle of outrigger is 5°

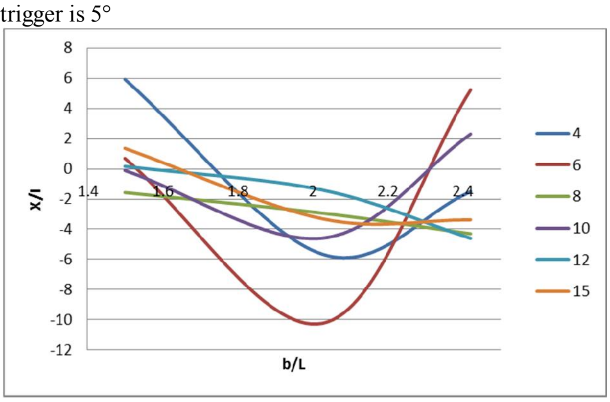

Fig.29 Figure of $\frac{x}{I_x}$ changes with b/L in the case the angle of outrigger is 10°

Fig.30 through33 display the curve of the roll restoring changing with b/L when the outriggers tilt an angle. Fig.30 show that the composite trimaran' roll restoring is influenced by the transverse spacing of the outriggers when the angle of the outriggers is -10°. The roll restoring has the same trend in all the cases and increase rapidly in the range of b/L< 2.0, then remains stable in the range of b/L>2.0. when the angle of the outriggers is -5°, we can get the conclusion that the roll restoring has the same trend with the transverse spacing. From the Fig.30 and Fig.31, we can find the roll restoring is a little bigger when the angle of the outriggers is -5°. From the Fig.32, the roll restoring increases with the transverse spacing in the range of b/L< 2.0 in all the cases when the angle of the outriggers is 5°. From the Fig.33, the roll restoring increases with the transverse spacing in all the range when the angle of the outriggers is 5°. From the Fig.32 and 33, the roll restoring is a little bigger when the angle of the outrigger is 5°.

From Fig.30 through 33, there is a significant result, suggesting that the roll restoring increase with the transverse spacing. In the most cases, the roll restoring increases rapidly in the range of b/L< 2.0 and remains stable in the range of b/L> 2.0. When the angle of the outriggers is±5°, the roll restoring is a little bigger.

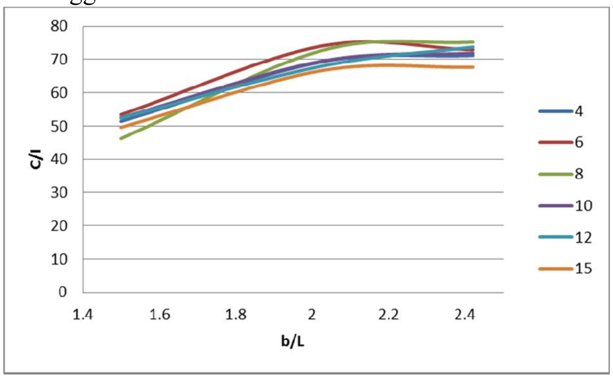

Fig.30 Figure of $\frac{c}{I_x}$ changes with b/L in the case the angle of outrigger is -10°

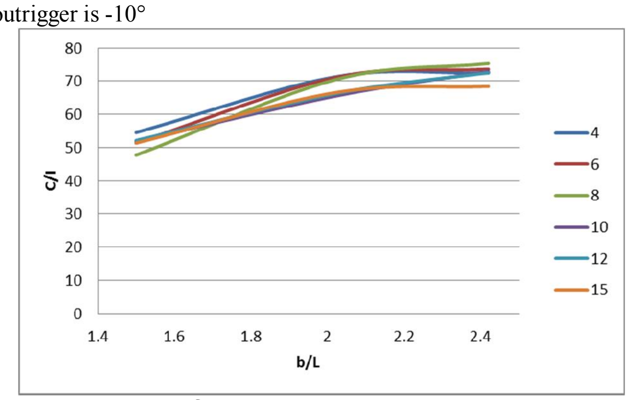

Fig.31 Figure of $\frac{c}{I_x}$ changes with b/L in the case the angle of outrigger is -5°

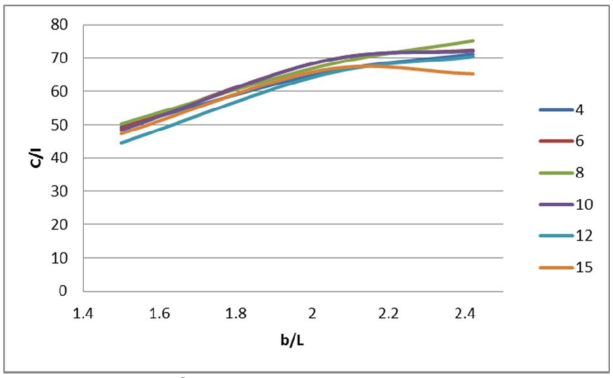

Fig.32 Figure of $\frac{C}{I_X}$ changes with b/L in the case the angle of outrigger is 5°

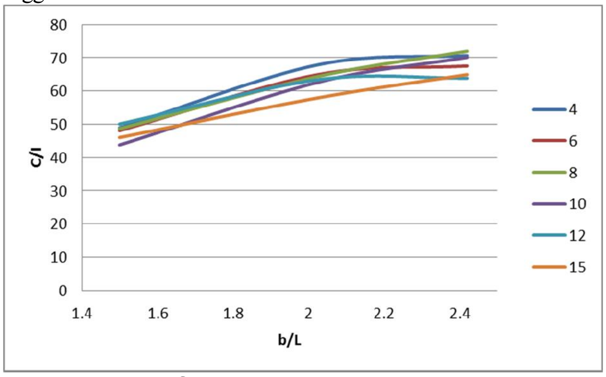

Fig.33 Figure of $\frac{C}{I_X}$ changes with b/L in the case the angle of outrigger is 10°

C. The increases of the Rolling Amplitude during the Roll Decay

In the roll decay experiments, the roll amplitude suddenly becomes small in 2-3 cycles and has a flat waveform (Fig.34) especially when the transverse spacing of the outriggers is 285mm and side hull tilt -5°. Make the roll extinction angle curve in Fig.34, through comparative analysis, we can get that when the side hull is inclined, there is an obviously flat waveform in 2-3 cycles. The amplitude of roll motion increase significantly in the back period. Through experimental observation and theoretical analysis, when the side hull tilted -5°, the wave induced by the hull is serious. The waves superpose and act on the composite trimaran as the transverse spacing is small.

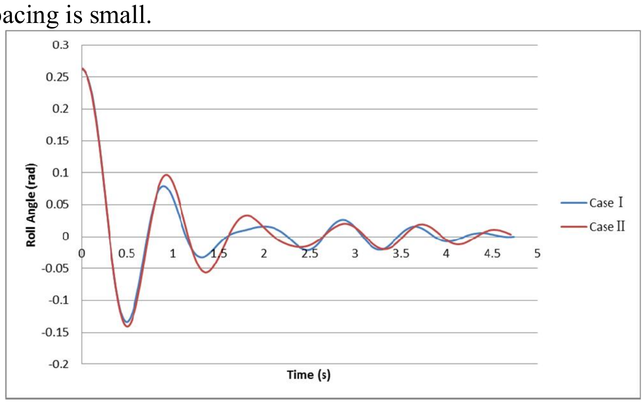

Fig.34 Free damping angle curve when l =285mm and side hull tilted -5°(Case Ⅰ is the curve of initial roll angle 15°and the inclination angle of the outriggers is -5; Case Ⅱ is the curve of initial roll angle 15° and the inclination angle of outriggers is 0°)

VI. CONCLUSION

The experimental analysis suggested that the position, draft and attitude of the composite trimaran outriggers will have a significant effect on vessel motion characteristics. It was found that linear damping and nonlinear damping change with draft, the position and attitude of the composite trimaran outriggers. It means that some configurations of outriggers would have a reducing effect on the motion characteristics of the vessel. This effect on seakeeping performance could be attributed to the different hydrodynamic interference effects for each configuration of the transverse spacing, attitude and draft.

The mathematical model of rolling motion was established considering both linear and nonlinear ship motion calculations. The identification software based on Support Vector Machine was programed. The results of identification have a good agreement with the experiment data, the relative error is less than 3.0% in most cases. Using the results of identification, we got the curves of roll hydrodynamic coefficients and their correlation coefficient changing with b/. Changes of roll hydrodynamic coefficients and their correlation coefficient are unlike monohull. This suggests that the hydrodynamic interactions occur in reality. These also investigate the effect of the attitude of the composite trimaran outriggers. In the result of free roll decay test, time histories of roll motion of the composite trimaran damp irregularly. There is an obviously flat waveform in 2-3 cycles. This paper can provide technical support in the optimization design of composite trimaran and the research of composite multi-hull ship.

Although we have carried out experiments of the rolling motion of a trimaran on numerous cases and got some typical roll motion mode of the composite trimaran, in order to investigate its more hydrodynamic characteristics, we feel that more detailed experiments should be carried out. In order to investigate the motion characteristics (including: pitch and heave, seakeeping performance on the waves, etc.) of the composite trimaran in waves, we should carry out more in-depth experimental and theoretical studies. Such as: the effect of the shape of main hull and outriggers and the configurations, the effect of the shape, size and position of hydrofoils etc. On this basis, the coupling effect of sway and maneuverability, sway and speed and powering in waves should be further studied.

ACKNOWLEDGMENT

This work is partially sponsored by Jiangsu Science and Technology University's "A Project Funded by "Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD)", for which the authors are grateful.

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Haitong Xu received a bachelor degree in Marine Engineering in 1983 from Yantai University, Shandong, China. From 2009 to2011, he worked in a shipyard.

He currently is a graduate student in the Jiangsu University of Science and Technology and will get his mater degree in Naval Architecture and Ocean Engineering in 2014. His research interests include theory and applications of system identification in the ship research, modeling and experimental research, ship motion and control, unmanned surface vessels and other high-performance vessel, methods of optimization, computer simulation.

Songlin Yang obtained Bachelor's degree of ship design and manufacturing major from Harbin engineering university, China, in Jan, 1982. After graduated, he worked as a ship constructor in 9318 shipyard in Jiangxi, Jiangxi province from Feb, 1982 to July, 1985. In Feb，1988，he obtained Master's degree of ship hydrodynamics major in Harbin engineering university, China. Subsequently he worked as a teacher in East China Shipbuilding Institute (now Jiangsu University of Science and Technology) until now. From Oct,2006 to Jan,2007,he has done an academic exchanges in the City University, London as a visiting senior research fellow.

He has been engaged in research on multi-disciplinary and multi-objective comprehensive optimization of ship, ship motion and control, theory and applications of system identification, modeling and experimental research, and high performance ship such as USV and UUV related fields. He has leaded more than 20 research projects including the national "863"programs, the national"973" important plan projects, the Royal Society projects, the international cooperation projects and various of province-level research projects, received provincial and prefectural awards several times.

Prof. Yang is a vice-chairman of ship design academic committee in Chinese Society of Naval Architecture and Marine Engineering, vice-chairman of Jiangsu hydrodynamics major committee, He served as a member of high performance ship groups of ship mechanics committee in Chinese Society of Naval Architecture and Marine Engineering. He is an editor of Journal of Jiangsu University of Science and Technology (Natural Science Edition).