アウトリガー付高速三胴船型の最適胴配置に関する研究

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はしがき

高速船あるいは高速艇の研究が盛んになり様々な提案がなされているが、本研究では船体の大型化や長距離外洋航行の点から有利と考えられる排水量型の高速船型を考える。排水量型に基づく高速船型は必然的に極細長船型になると考えられるが、この場合問題になるのが復原性であり一般には双胴船型とすることによりこの問題をクリアしている。本研究では双胴ではなく主船体の両舷に小型のアウトリガーを持つ高速三胴船型を扱う。三胴船型の場合には主船体との造波干渉が期待でき、造波理論と非線形計画法により最適な胴配置を計算することができる。本研究はこのような三胴船の最適胴配置問題および模型試験 (抵抗試験、波形解析、姿勢および沈下の計測) による抵抗特性の把握をその対象としてる。

三胴船型の抵抗特性に関する主要な研究は国内においては瀬尾、成田等による一例のみであり、その後この種の研究は実施されていない。諸外国では関連する少数の研究があるが、本研究とは観点が全く異なる。特に本研究で対象としているような小型のアウトリガーを持つ形式の三胴船型に関しては研究実施例がない。また非線形計画法の利用による最適胴配置の計算は例がなく、その検討は造波干渉に関する新たな知見を与えるものと考えられる。本研究ではまず基礎的検討として数学船型の例を示し、次に実用的高速船型の例を示すことにより抵抗特性から見たその実用性を検討する。

研究組織

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研究成果

1. アウトリガー付き三胴船型の胴配置に関する造波抵抗極小化の研究

2. Fundamental Study on Optimum Position of Outriggers of Trimaran from View Point of Wave Making Resistance

3. Optimum Positions of Outriggers of High-Speed Trimaran with Slender Main Hull from Viewpoint of Wave Making Resistance

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Optimum Positions of Outriggers of High-Speed Trimaran with Slender Main Hull from Viewpoint of Wave Making Resistance

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ABSTRACT

In the present study, a trimaran with small outriggers at both sides is introduced as a high-speed ship of multihull type. In the case of the trimaran, the wave making interaction between the main hull and outriggers is expected to reduce the wave making resistance. For a practical slender main hull, positions of small outriggers are optimized from the viewpoint of wave making resistance, and models are tested in a towing tank to verify hydrodynamical effects of outriggers.

1 Introduction

In order to design high-speed vessels, many ideas based on unconventional concepts have been proposed in recent years. New concepts of high-speed vessels based on the conventional displacement type have also been proposed and studied [1),2),3),4)] with the aim of upscaling such vessels and rendering them practical for long-distance voyages. In these vessels based on the displacement concept, very slender hulls are generally employed. For such hulls, however, serious stability problems are known to occur ; a multihull vessel, for example, a catamaran, may be used to avoid such problems.

In this paper, a trimaran with small outriggers at both sides is introduced in place of the catamaran. In the case of this trimaran, the wave making interaction between the main hull and outriggers is expected to reduce the wave making resistance. In previous work concerning the trimaran with small outriggers, fundamental studies on the optimum positions of outriggers were carried out [5)] from the viewpoint of wave making resistance, in which mathematical forms were employed for the main hull and outriggers. In the present study, a practical high-speed hull of slender displacement type proposed by Takarada et al.[1),2)] is introduced as the main hull, and studies similar to the previous one are carried out. Positions of small outriggers are optimized from the viewpoint of the minimization of wave making resistance by means of nonlinear programming. Model tests based on the optimization results are carried out to verify hydrodynamical effects of outriggers, including towing tests, wave analyses, and measurements of trim and sinkage.

2 Calculation of optimum positions of outriggers

A trimaran which consists of a main hull and two small outriggers, as shown in Fig. 1, is investigated in this work. For this type of trimaran, the positions of the outriggers are optimized in order to minimize the wave making resistance, as explained above. Before describing the treatment of the problem, the coordinate system and some definitions are introduced. Length, breadth and draft of the main hull are defined as L, B, and T, respectively, and those of the outriggers are defined as L_0, B_0, and T_0, respectively. The main hull and each outrigger have displacements ∇ and ∇_0, respectively. The coordinate system normalized by $\ell = L/2$ with x positive toward the bow, y athwartship, and z positive upward is taken, as shown in Fig. 1, in which the origin is placed on the still water plane at the midship of the main hull. The center of the outrigger on the port side is defined as (x_0, y_0) and that of the outrigger placed at the opposite position, $(x_0, -y_0)$. For the sake of convenience, the following normalized ratios are used.

$$b = (B/2)/\ell = B/L \tag{1}$$

$$t = T/\ell \tag{2}$$

$$\lambda_0 = (L_0/2)/\ell = L_0/L \tag{3}$$

$$b_0 = (B_0/2)/\ell = B_0/L = \lambda_0(B_0/L_0) \tag{4}$$

$$t_0 = T_0/\ell \tag{5}$$

In this paper, the Froude number is defined using the length of the main hull as

$$F_n = U/\sqrt{gL}, \tag{6}$$

where U is the forward velocity of the trimaran.

For the sake of simplicity, both the main hull and the outrigger are approximated as the following elementary ships, which are similar to those used in the previous study [5]. The equation of the main hull is given as

$$y = f(x)g(z), \tag{7}$$

and that of the outriggers is given as

$$y \pm y_0 = f_0(x - x_0)g_0(z). \tag{8}$$

In equation (7) for the main hull, the shape of the water line $f(x)$ can be approximated by a Fourier series as

$$f(x) = \pm \sum_{n=1}^{N} \left(a_n \cos \frac{2n-1}{2}\pi x + b_n \sin n\pi x \right), \tag{9}$$

and the shape of the frame line $g(z)$ can also be approximated by a parabola with order β as

$$g(z) = 1 - \left| \frac{z}{t} \right|^{\beta} \tag{10}$$

Shapes of the water line $f_0(x - x_0)$ and the frame line $g_0(z)$ of the outriggers in equation (8) are expressed using similar forms.

Based on the above expressions for the trimaran, the optimization problem for the positions of the outriggers can be formulated. In the present optimization problem, the objective function is defined as the wave making resistance coefficient

$$C_w = 8\pi\gamma_0^2 \int_0^{\pi/2} (\{P(\theta)\}^2 + \{Q(\theta)\}^2) \sec^3\theta d\theta, \tag{11}$$

where

$$\gamma_0 = g\ell/U^2 = 1/2F_n^2. \tag{12}$$

In the optimization process, this wave making resistance coefficient (11) is evaluated by means of Michell-Havelock's linear wave making resistance theory, because very slender hull forms are generally employed for high-speed ships of displacement type. In the case of the linear theory, amplitude functions $P(\theta)$ and $Q(\theta)$ can be represented by a linear superposition such as

$$\left.\begin{matrix} P(\theta) \\ Q(\theta) \end{matrix}\right\} = \left\{\begin{matrix} P_M(\theta) \\ Q_M(\theta) \end{matrix}\right\} + \left\{\begin{matrix} P_0(\theta) \\ Q_0(\theta) \end{matrix}\right\}. \tag{13}$$

The first term of the right-hand side of equation (13) represents the wave making effect of the main hull, and the second term represents the total wave making effect of the outriggers at port and starboard sides. Respective amplitude functions can be obtained using Michell-Havelock's linear theory as follows.

$$\begin{aligned} \left.\begin{matrix} P_M(\theta) \\ Q_M(\theta) \end{matrix}\right\} = & -\frac{1}{2\pi}\int_{-1}^{1} \frac{\partial f(x)}{\partial x} \begin{matrix} \cos \\ \sin \end{matrix} (\gamma_0 x \sec\theta) dx \cdot \int_{-t}^{0} g(z) e^{\gamma_0 z \sec^2\theta} dz \\ & + m e^{\gamma_0 z_o \sec^2\theta} \left\{ \begin{matrix} \cos \\ \sin \end{matrix} (\gamma_0 x_F \sec\theta) - \begin{matrix} \cos \\ \sin \end{matrix} (\gamma_0 x_A \sec\theta) \right\} \end{aligned} \tag{14}$$

$$\begin{aligned} \left.\begin{matrix} P_0(\theta) \\ Q_0(\theta) \end{matrix}\right\} = & -\frac{1}{\pi}\cos(\gamma_0 y_0 \sec\theta \tan\theta) \int_{x_0-\lambda_0}^{x_0+\lambda_0} \frac{\partial f_0(x - x_0)}{\partial x} \begin{matrix} \cos \\ \sin \end{matrix} (\gamma_0 x \sec\theta) dx \\ & \cdot \int_{-t_0}^{0} g_0(z) e^{\gamma_0 z \sec^2\theta} dz \end{aligned} \tag{15}$$

As shown in the subsequent sections, the slender main hull adopted in this study has a small ovoid at its bottom, which is hydrodynamically formed by a point source and a point sink. In order to express its wave making effect, the 2nd term is added to the right-hand side of equation (14), where z_o is the center depth of the ovoid, x_F is the position of the point source, X_A is the position of the point sink and the respective strengths are expressed as $\pm m$. Formulae for numerical calculations of these amplitude functions can easily be obtained by substituting equations (9) and (10) into equations (14) and (15) [3),4)].

The present optimization problem can be described as follows : to find the optimum position of outriggers (x_0, y_0) which minimizes the wave making resistance coefficient C_w under some design constraints. Since the wave making resistance coefficient C_w is a non-linear function with respect to x_0 and y_0, our problem becomes a nonlinear programming problem with two design variables. This nonlinear optimization problem is solved under the following simple constraints for design variables x_0 and y_0.

$$x_\ell < x_0 < x_u, \qquad y_\ell < y_0 < y_u \tag{16}$$

The respective upper and lower bounds can be selected as practical ranges. In the following section concerning numerical examples, the optimization of y_0 for a given value of x_0 is also carried out in order to discuss the variation of the optimum transverse position of outriggers along the longitudinal direction. Thus the problem is simplified to have only one design variable and it can easily be solved by means of a simple algorithm for one directional search. In this study, the optimization is carried out by means of SUMT [6] with Zangwill's direct search method [7].

3 High-speed trimaran with slender main hull

3.1 Numerical examples of optimization

In the previous study [5], the optimization problem of outrigger positions was discussed with respect to a trimaran with a simple mathematical form. For practical purposes, however, the optimization of the main hull should be considered. In the present study, the super-high-speed monohull investigated by Takarada et al. [1),2)] is employed as the main hull, and the positioning of the outriggers is discussed from the viewpoint of wave making resistance.

In research by Takarada et al., a study on the resistance and propulsive characteristics of an about 10,000MT displacement, monohull, and 50 knots speed container ship with superconducting propulsion motors was carried out. By means of theoretical and experimental approaches, a new hull with small resistance has been developed, applying the semi-submerged ship theory. This slender main hull has the midship section shown in Fig. 2, a small ovoid at its bottom, a small entrance angle at its water line and a whaleback side profile at its bow to suppress spray making phenomena. In the optimization process in the present work, its water line is approximated by equation (9) and its frame line is approximated by equation (10) with $\beta = 1$. The water line of the main hull is compared with its approximation in Fig. 3. In the present examples, the outrigger is selected as a mathematical form with parameter values 1/3 those of the main hull, which is symmetric fore and aft, as follows.

$$y \pm y_0 = \pm b_0 \cos \frac{\pi}{2\lambda_0}(x - x_0)\left(1 + \frac{z}{t_0}\right) \tag{17}$$

$$\lambda_0 = 1/3, \qquad b_0 = (1/3)b, \qquad t_0 = (1/3)t \tag{18}$$

The midship section of the outrigger is also shown in Fig. 2. Particulars of models of the main hull and the outrigger are shown in Table 1.

Optimization results of positions of the outriggers are shown in Fig. 4, in which design Froude numbers are 0.45 and 0.58, where the latter corresponds to the original design speed of the main hull, that is, 50 knots for the super-high-speed monohull. In this figure, results of two kinds of optimization problem are included. The first one is the optimization problem of y_0 for a given value of x_0, which is carried out to discuss the variation of the optimum positions of the outriggers along the longitudinal direction. The variation of optimum positions differs for the two design Froude numbers. In the case of design F_n=0.45, the outriggers get nearest to the main hull at 0.4 in fore part and at 0.6 in aft part respectively. In the case of design F_n=0.58, however, the optimization results maintain almost the same positions along the longitudinal direction. These results may be related to the fact that diverging wave components become more and more dominant at higher Froude numbers such as F_n=0.58. In the second problem, both design variables x_0 and y_0 are optimized, with the results shown by the large open circle and square in Fig. 4. In this problem, the following constraints are imposed to keep the total length on the still water plane from exceeding the length of the main hull.

$$-2/3 < x_0 < 2/3, \qquad 0.15 < y_0 < 0.5 \tag{19}$$

As shown in Fig. 4, for both design Froude numbers, optimum positions are obtained at inner positions of the constraint (19). Based on these numerical results, the following model tests are planned and executed.

3.2 Models and experimental results

Resistance characteristics of the trimaran with the main hull and small outriggers at both sides are investigated by model tests in order to verify the hydrodynamical effects of outriggers. In these experiments, towing tests, wave analyses, and measurements of trim and sinkage are carried out for a trimaran model for which the position of outriggers can be changed freely. All model tests are carried out under free trim conditions. Particulars of the main hull and the outrigger are given in Table 1. At the protruding part of the bow ovoid and S.S. $9\frac{1}{4}$, namely, 30mm behind F.P. of the main hull and 50mm behind F.P. of the outrigger, studs of height 2mm are fitted at 10mm intervals as turbulence stimulators.

Model names and positions of outriggers are given in Table 2 and illustrated in Fig. 5. The model name SHH-0 is assigned to the main hull without outriggers, namely, the monohull model. In the case of model SHTR-0, the outriggers are arranged as far away from the main hull as possible under experimental conditions in order to eliminate the effect of wave making interaction between the main hull and the outriggers. Models SHTR-1 of design F_n=0.45 and SHTR-2 of design F_n=0.58 are trimarans with outriggers at the optimum position based on the numerical examples shown in the previous section.

Residuary resistance coefficients C_r obtained from towing tests using Schoenherr's friction coefficients are shown in Fig. 6. In the higher Froude number range, residuary resistance coefficients of every trimaran model become higher than that of the monohull model SHH-0, as shown in Fig. 6. At both design Froude numbers, however, residuary resistance coefficients of model SHTR-1 and model SHTR-2 are smaller than that of model SHTR-0, in which the effects of the optimum positions of outriggers are verified. Especially in the case of model SHTR-1, the coefficient at design F_n=0.45 is slightly smaller than that of the monohull model SHH-0.

In Figs. 7 and 8, results of measurements of trim and sinkage, respectively, are shown. In the case of trim, marked differences between models are not observed. In the case of sinkage, however, the result for model SHTR-1 is smaller than those for models SHH-0 and SHTR-2 for almost all F_n. As is well known, large trim and/or sinkage are related to the increase of total resistance. In a practical sense, however, the results for the trim and sinkage shown here are not too large, because the main hull is well optimized as a practical high-speed hull.

For the purpose of examining whether the linear wave making resistance theory adopted in this study is effective to optimize outrigger positions, theoretical wave making resistance coefficients C_w based on the linear theory are compared with residuary resistance coefficients C_r and wave pattern resistance coefficients C_{wp} determined from results of wave analyses shown in Fig. 9 for both models SHTR-1 and SHTR-2. Because of the employment of the linear theory and the approximation of the main hull form based on the elementary ship assumption expressed in equations (7), (9) and (10), quantitative agreement between theoretical results and experimental results is poor, as shown in Fig. 9. However, qualitative tendencies in respective coefficients for the differences of performance of both models are almost in agreement. Based on these results, it can be considered that the linear wave making resistance theory plays an effective role in the optimization of outrigger positions at the initial design stage of practical trimarans. In order to obtain an accurate estimation of the fluid resistance acting on the trimaran, the complicated flow interaction phenomena between the main hull and the outriggers must be taken into account by means of more sophisticated methods of numerical analysis such as the Rankine source panel method or CFD.

Finally, in order to investigate whether the positions of outriggers based on the present optimization results are actually optimum, towing tests of trimarans having outriggers at the 15 points illustrated in Fig. 10 are carried out at F_n= 0.45 and 0.58. These results are shown in Figs. 11 and 12 in terms of the residuary resistance coefficients. Among the results in the case of F_n=0.45, the residuary resistance of model SHTR-1 optimized at F_n=0.45 is almost minimum, but it can be considered that there is a suitable position at the stern which shows equivalent resistance characteristic to that of model SHTR-1. In the case of F_n=0.58, the resistance characteristic of model SHTR-2 optimized at F_n=0.58 is slightly worse than those of model SHTR-1 and a few positions at the stern. Generally speaking, however, the present optimization results show suitable outrigger positions in comparison with the results for trimarans without optimization.

4 Conclusions and acknowledgements

In the previous and present papers, a trimaran with small outriggers at both sides has been proposed and studied. Positions of these small outriggers have been optimized to minimize the wave making resistance due to the wave making interaction between the main hull and the outriggers. In the previous fundamental study [5)], mathematical forms were adopted for the main hull and outriggers. In the present study, however, the practical super-high-speed hull investigated by Takarada et al. [1),2)] was employed as the main hull, and model tests were carried out to verify the hydrodynamical effects of the outriggers. The main conclusions of the present paper are summarized as follows.

1. In the higher Froude number range, residuary resistance coefficients of the trimaran become higher than that of the monohull. However, at respective design Froude

numbers, coefficients of the trimaran with the optimum positions of outriggers are smaller than the results for the trimaran without optimization.

2. It is concluded from the results of model tests that the trimaran with the optimum positions of outriggers can be expected to have reduced wave making resistance due to the wave making interaction between the main hull and the outriggers.

3. It can be considered that the linear wave making resistance theory plays an effective role in the optimization of outrigger positions at the initial design stage of practical trimarans.

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Table 1: Particulars of main hull and outriggers (Super-high-speed hull)

Particulars	Main Hull		Outriggers	
Length	L	1.200 m	L_0	0.400 m
Breadth	B	0.090 m	B_0	0.030 m
Draft	T	0.051 m	T_0	0.017 m
Order of Parabolic Frame Line	β	-	β	1
Displacement Volume	∇_M	0.002104 m^3	∇_0	0.000065 m^3
Displacement Length Ratio	∇_M/L^3	0.001215	∇_0/L_0^3	0.001015
Wetted Surface Area	S_M	0.1576 m^2	S_0	0.0155 m^2
Block Coefficient	C_b	0.3813	C_{b0}	0.3183
Prismatic Coefficient	C_p	0.6757	C_{p0}	0.6366
Midship Coefficient	C_m	0.5643	C_{m0}	0.5000
Water Plane Coefficient	C_w	0.7200	C_{w0}	0.6366
Displacement Volume of Trimaran			∇	0.002234 m^3
Wetted Surface Area of Trimaran			S	0.1885 m^2

Table 2: Model names and positions of outriggers

Model Name	Design F_n	x_0	y_0
SHH-0	0.58	without outriggers	
SHTR-0	-	0.000	±0.900
SHTR-1	0.45	0.52	±0.253
SHTR-2	0.58	-0.13	±0.395

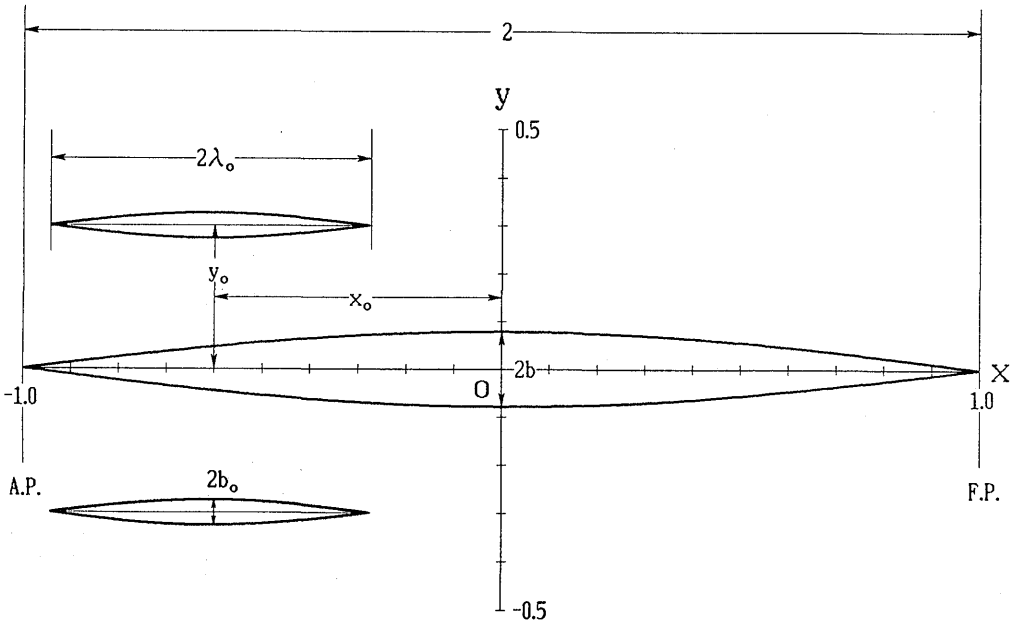

Fig. 1 Coordinate system for arrangement of trimaran

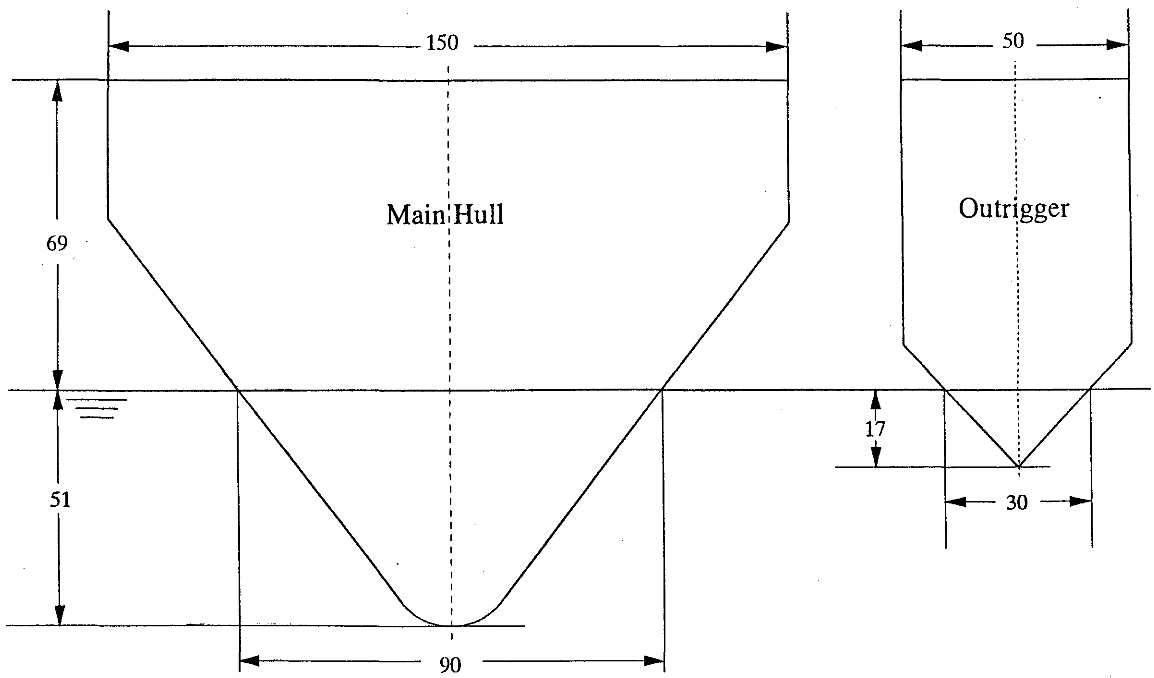

Fig. 2 Midship sections of model of main hull and outrigger

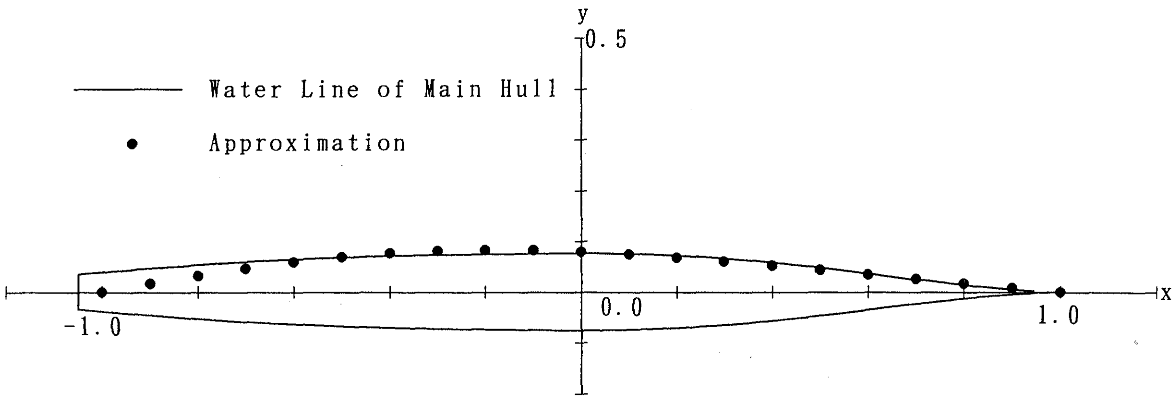

Fig. 3　Approximation of water line of main hull

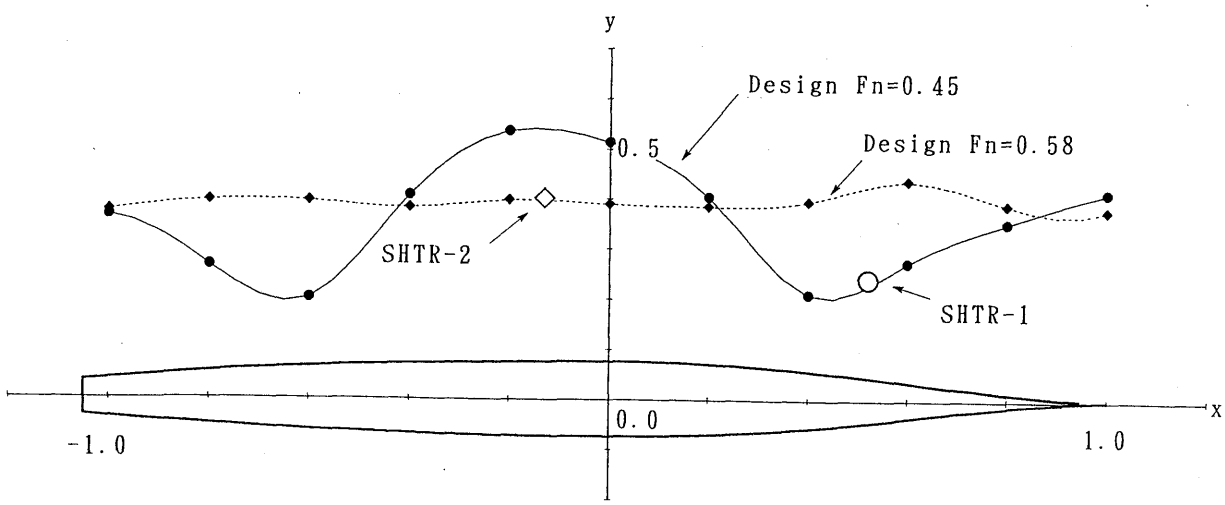

Fig. 4　Optimum positions of outriggers

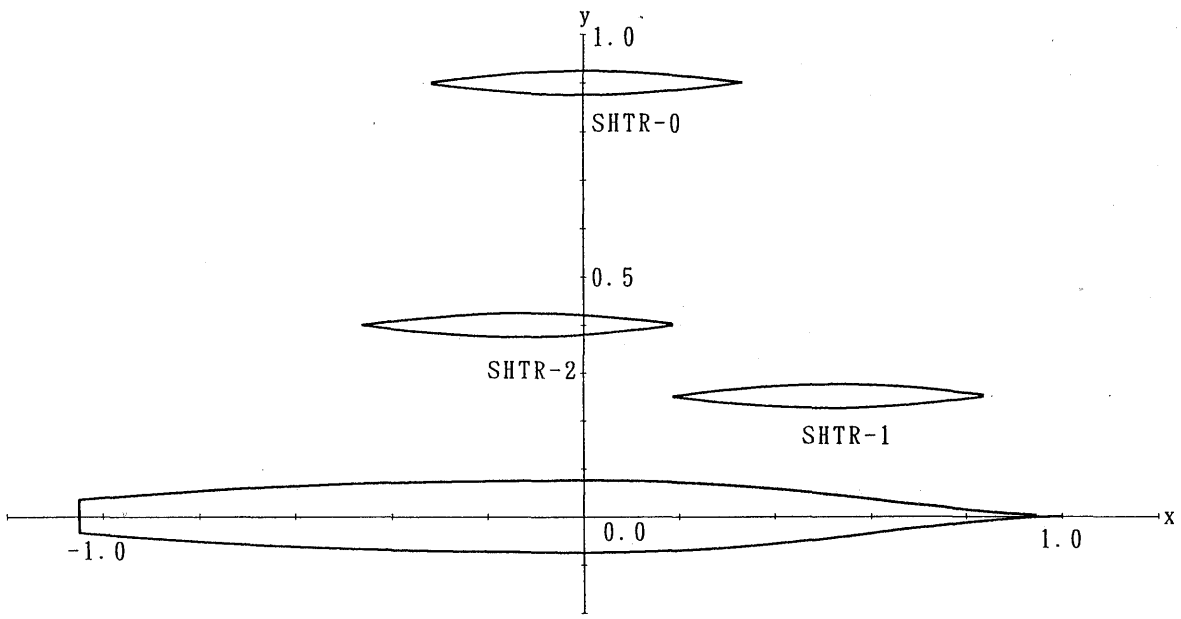

Fig. 5 Positions of outriggers of trimaran models

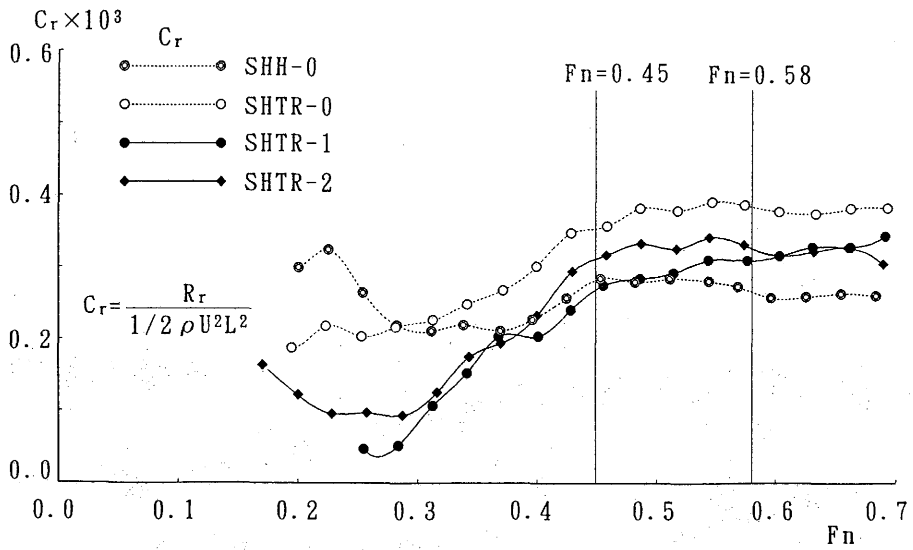

Fig. 6 Comparison of residuary resistance

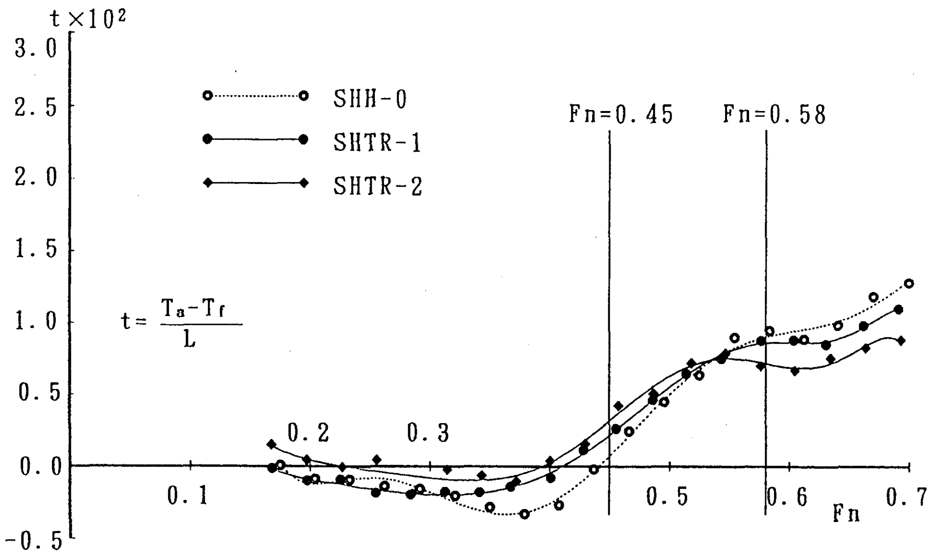

Fig. 7 Comparison of trim

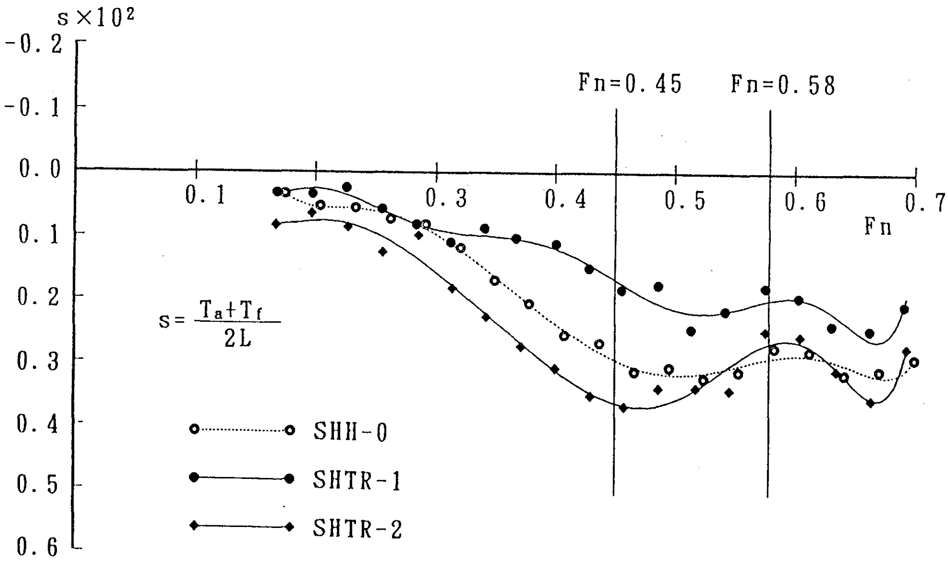

Fig. 8 Comparison of sinkage

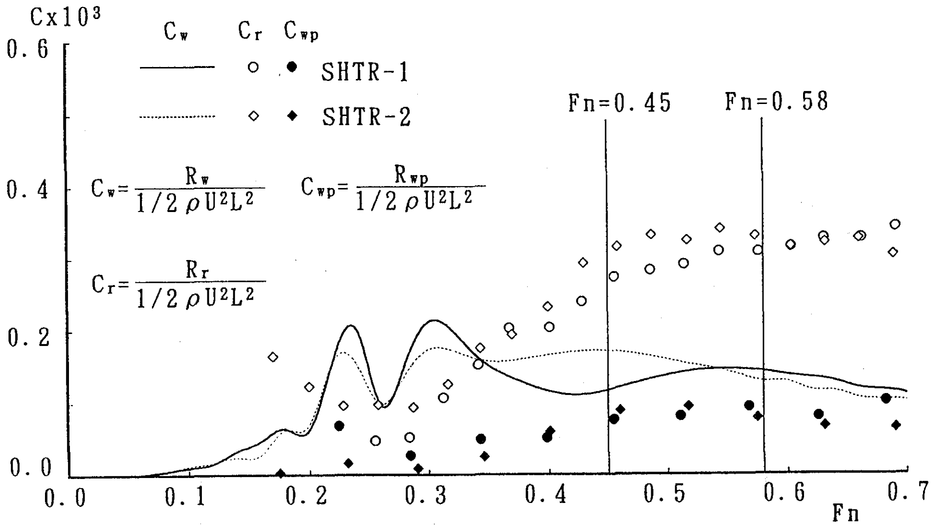

Fig. 9 Comparison of experimental results and theoretical wave making resistance

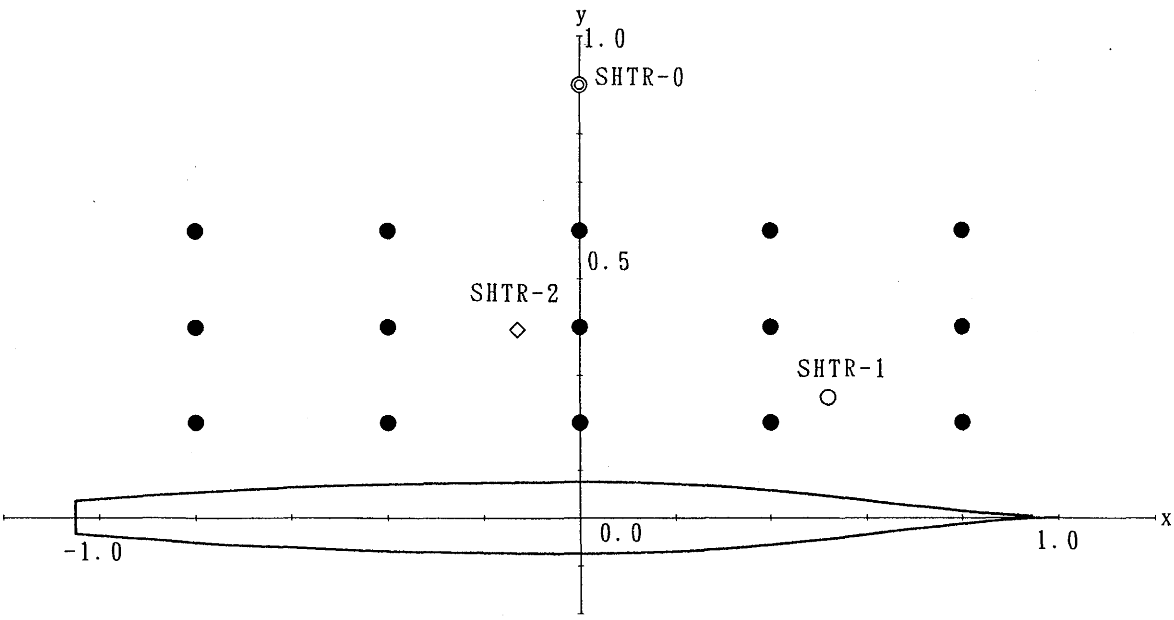

Fig. 10 Positions of outriggers of trimaran models

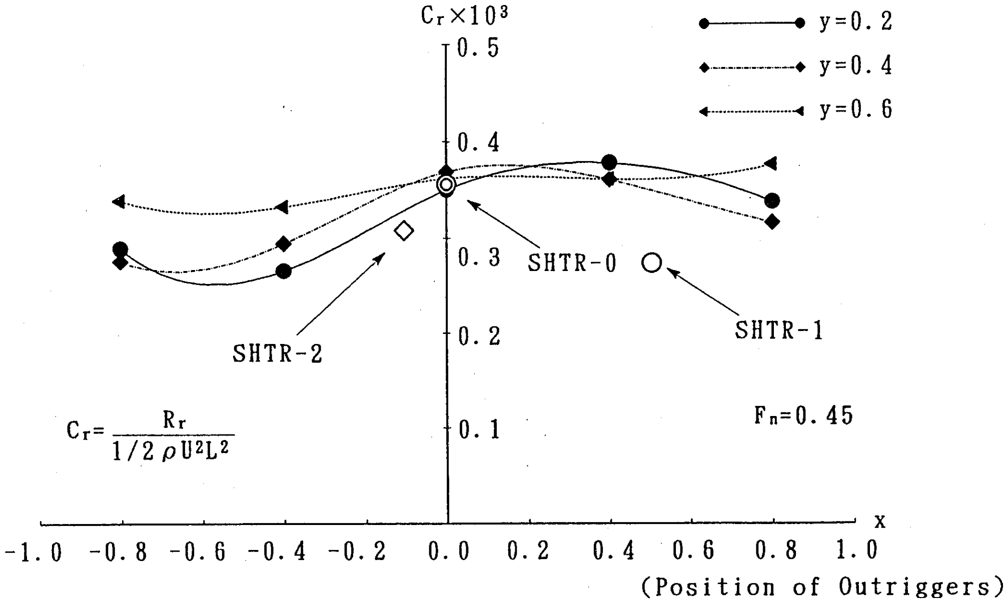

Fig. 11 Comparison of residuary resistance at $F_n = 0.45$

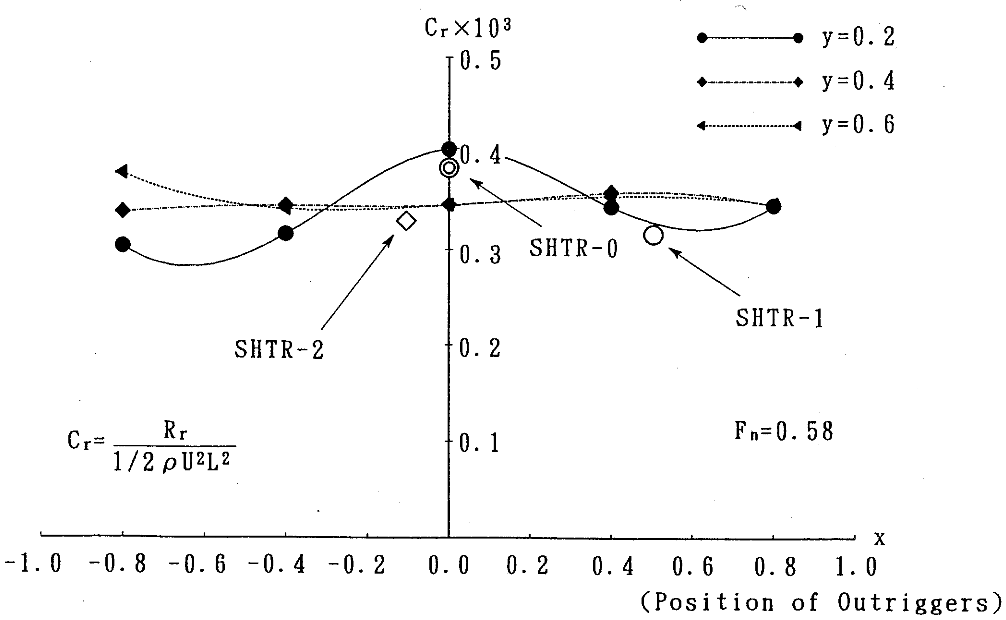

Fig. 12 Comparison of residuary resistance at $F_n = 0.58$