

Minimum Resistance Hull Form of Planing Craft with Controlled Trim Angle

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Abstract

This paper is concerned about the determination of optimum planing craft hull form having the minimum resistance in still water within high speed range for a controlled less trim angle change, because pilots and crews want planing crafts keeping less trim angle change although less trim angle change requires higher resistance.

SUMT method is applied to determine the optimum planing craft hull form parameters within towing model test data. For any shape of hull forms under satisfied requirement's conditions, we can expect to obtain the optimum planing craft hull form keeping the small change of trim angle while planing at high speed.

Introduction

Thirteen kinds of models were tested, which include wide and narrow transom widths, large and small initial trims, high and low chine heights etc.. Applying principal component analysis we classified the models on two dimensional coordinates.

The abscissa means the first principal component axis Z_1 and the ordinate the second one Z_2 . Then, applying factor analyses we tried to extract hull form's five elements. Referring to five elements, we examined all 13 kinds of hull forms having the minimum resistance obtained by a nonlinear optimization technique. The minimum values are obtained by Zangwill's method (1967) which enables calculation steps to be stable. As a result, through restrictions of decreasing the maximum trim angle change of planing hull in high speed range to 270, 240, 180 minutes, the minimum resistance hull form is reasonably determined.

Nomenclature

B : Variance Covariance Matrix made from hull form parameters.

C_t : resistance coefficient. $C_t = R / (1/2) \rho V^2 \cdot \nabla^{2/3}$

F_r : Froude number. $F_r = V / \sqrt{\nabla^{1/3} \cdot g}$

$f(x)$: objective function.

g : accerelation of gravity.

$g_i(x)$: i th restrictive condition.

N : number of test data.

Received, 1995. 9. 8

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$p(x)$: modified objective function.

R : resistance.

r_k : perturbation coefficient at k step.

v : speed.

x : hull form parameter vector by the element x_i .

X^2 : statistical distribution.

x_i : i th non-dimensional hull form parameter.

\bar{x}_i : mean value of x_i by N .

z_i : i th principal component axis or its score.

θ : initial trim angle.

ρ : density.

σ_{x_i} : standard deviation of x_i .

ΔD : non-dimensional draft change at the deepest point of transom, as positive for decreasing draft.

Δx : deviation vector by the element $x_i - \bar{x}_i$.

$\Delta \theta$: trim angle change (min.), as positive for bow up.

∇ : displacement volume.

Classification of Models and Hull Form's five elements

Thirteen kinds of tested models are classified as Fig. 1 by principal component analysis (Yoshida, 1976a) as Z_1 and Z_2 .

Displacements and center of gravities of a 2.5 m length model are set six ways. We call the model group No. 1 to 6 the first cluster, No. 7 to 12 the second cluster, and so on. A hull form is pictured on its cluster, and 13 kinds of clusters or models form a shape like ellipse. In this hull form scale, the transom's half width b_1 equals to 1.

Applying factor analyses (Yoshida, 1976a), we try to extract hull form's five elements that conform the hull form. As a result, five elements consist of (1) figure containing total length, half width at 0rd. 5 and 2, and displacement, (2) chine-height at 0rd. 10 (stern), 5 and 2, (3) initial trim angle, (4) bow-shape containing keel-height at 0rd. 2 and 0 (bow) and chine-height at 0rd. 2 and (5) combination of total length and curvature of transom. These give us convenient rating scales to compare hull forms.

Relations Between Trim Angle Change and Total Resistance Coefficient in High Speed Range

Total resistance coefficient ($R/0.5\rho V^2\nabla^{2/3}$) is affected by trim angle change $\Delta\theta$ in high speed range (Yoshida, 1976a). The correlation coefficients among total resistance coefficient $C_{t3.5}$ at Froude number ($F_F = V/\sqrt{\nabla^{1/3} \cdot g}$) = 3.5 and trim angle change $\Delta\theta_{2.5}$, $\Delta\theta_{3.0}$ and $\Delta\theta_{3.5}$ at $F_F = 2.5, 3.0$ and 3.5 equal to -0.76 , -0.71 and -0.60 , respectively. Hence $C_{t3.5}$ has the

strongest relation with $\Delta\theta_{2.5}$.

Decision of the Minimum Resistance Hull Form

Changing model's principal dimensions, the minimum resistance hull form will be searched by SUMT method (Sequential Unconstrained Minimization Technique) (Nagai, 1977), which is one of the nonlinear optimization techniques, for all kinds of classified models. We examine obtained hull forms under restrictions of trim angle changes or without restrictions, comparing them with the original hull form, and using hull form's five elements.

As for SUMT method, an optimization problem of "minimization of objective function $f(x)$ under restrictions of $g_i(x) \geq 0$, $i=1, 2, 3, \dots, N$ " is transformed to the problem of "minimization of $P(x)$ without restriction" to get the minimum value.

$$P(x) = f(x) + r_k \sum_{i=1}^N 1/g_i(x).$$

$P(x)$ is designated as modified objective function. The minimum value is obtained by Zangwill's method which enables calculation steps to be stable.

Now, we list an objective function and restrictive conditions.

Objective function

$$f(x) = \text{total resistance coefficient at } F_F = 3.5 (= C_{t3.5}) = \beta_1 + \sum_{i=2}^{15} \beta_i x_i,$$

(Nagai, 1975), where $x_{13} = x_7^2$, $x_{14} = x_7 \cdot x_{11}$ and $x_{15} = x_{11}^2$. The variables from x_2 through x_{12} are modified to take positive values like ones of linear optimization problem.

$$x_i = X_i - \bar{X}_i + a_i \sigma_i, \quad i=2, 3, \dots, 12.$$

Mean value \bar{X}_i and standard deviation σ_i are made by 78 sets of hull form parameters X_i ($i=2, 3, \dots, 12$). a_i is the constant that is multiplier to σ_i to give the inferior and superior limits of x_i . The quadratic variables x_{13} , x_{14} and x_{15} are also taken positive values. $a_i = 2.0$ except 12th cluster. In the 12th cluster $a_7 = 2.5$ and $a_{10} = 3.0$.

Restrictive conditions

(I) Hull form parameters etc. exist within experimental data's range

$$\Delta x^T B^{-1} \Delta x \leq \chi^2(14, 0.05).$$

(II) Hull form parameters etc. keep each mean value's neighbourhood

$$0 \leq x_i \leq 2a_i \sigma_i, \quad i=2, 3, \dots, 15.$$

(III) Hull form parameters etc. remain inside the cluster

For example, in view of multidimension, the first cluster's similar hull forms are conditioned by the outward planes that contain No. 6 test model at center. Each outward plane is recognized by calculating its intercepts on principal component axes Z_1 , Z_2 and Z_3 . Z_i 's

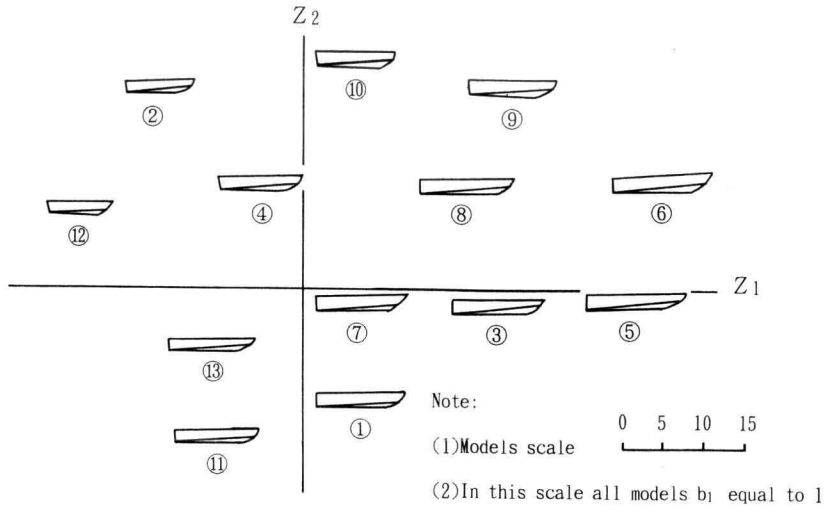


Fig. 1. Classification of models

principal component axis consists of the variables x_2 to x_{15} .

The result is shown as the cluster in Fig. 3 of p. 54 of the reference (Yoshida, 1976b). This figure differs from Fig. 1. In case of using quadratic equations, main factor of expressing hull form character Z_1 is transom width, followed by initial trim Z_2 and chine Z_3 . Z_1 , Z_2 and Z_3 are independent factors each other.

Concerning Z_1 and Z_2 , we have

$$\begin{aligned} 1 - (Z_1/a_1 + Z_2/a_2) &\geq 0, \\ 1 - (Z_1/a_3 + Z_2/a_4) &\geq 0, \\ 1 - (Z_1/b_1 + Z_2/b_2) &\leq 0, \\ 1 - (Z_1/b_3 + Z_2/b_4) &\leq 0, \end{aligned}$$

where $a_1=0.92547$, $a_2=-27.13450$,
 $a_3=0.41436$, $a_4=-2.04928$,
 $b_1=0.74558$, $b_2=-65.76129$,
 $b_3=0.44520$, $b_4=-3.89285$.

We have similar equations as above ones between Z_2 and Z_3 , and between Z_3 and Z_1 . Concerning Z_2 and Z_3 ,

$$\begin{aligned} 1 - (Z_2/a_1 + Z_3/a_2) &\geq 0, \\ 1 - (Z_2/a_3 + Z_3/a_4) &\geq 0, \\ 1 - (Z_2/b_1 + Z_3/b_2) &\leq 0, \\ 1 - (Z_2/b_3 + Z_3/b_4) &\leq 0, \end{aligned}$$

where $a_1=2.27207, \quad a_2=-1.71477,$
 $a_3=2.06565, \quad a_4=-1.22895,$
 $b_1=1.98010, \quad b_2=-1.59003,$
 $b_3=1.79135, \quad b_4=-1.19695.$

Concerning Z_3 and Z_1 ,

$$\begin{aligned} 1-(Z_1/a_1+Z_3/a_2) &\geq 0, \\ 1-(Z_1/a_3+Z_3/a_4) &\geq 0, \\ 1-(Z_1/b_1+Z_3/b_2) &\leq 0, \\ 1-(Z_1/b_3+Z_3/b_4) &\leq 0, \end{aligned}$$

where $a_1=1.00296, \quad a_2=-22.19370,$
 $a_3=0.83203, \quad a_4=-2.44817,$
 $b_1=0.76803, \quad b_2=-54.39666,$
 $b_3=0.65007, \quad b_4=-3.79811.$

The fourth principal component score Z_4 is set as

$$-0.66523 \leq Z_4 \leq -0.43843.$$

(IV) Limitation against the maximum trim angle change level

As limitation against the maximum trim angle change level, $\Delta\theta_{2.5}$ is used by following equation. (Nagai, 1975)

$$\Delta\theta_{2.5} = \beta'_1 + \sum_{i=2}^{15} \beta'_i x_i,$$

Using SUMT method,

$$|\Delta P/P(x, r_k)| \leq 10^{-4}$$

is set for convergence coefficient. Initial value of perturbation r_k is set at 10^{-3} .

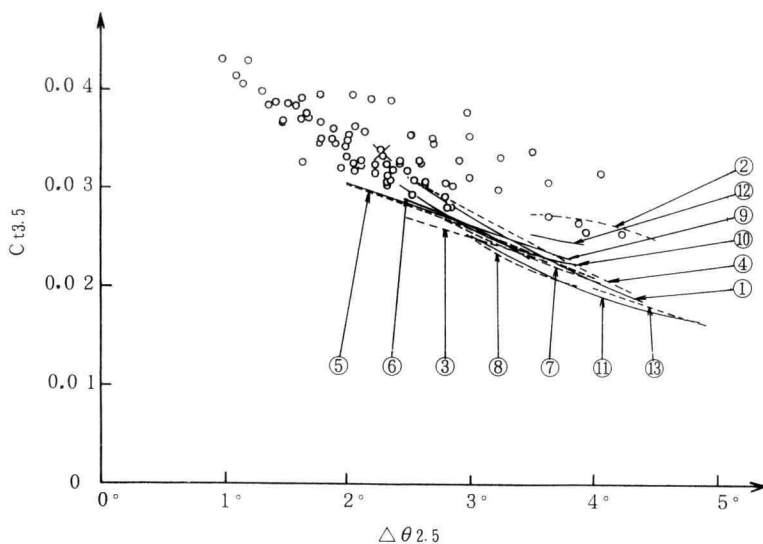
(1) Minimum resistance hull form satisfied with three conditions concerning figure, initial trim and chine etc., say, from (I) through (III) conditions.

The hull forms satisfied with the requirements are expressed by each cluster. Good examples showing hull form's characteristics are ⑥ 6th cluster containing hull forms having smaller transom or longer hull, ⑫ 12th cluster containing hull forms having larger transom or shorter hull, ① 1st cluster containing hull forms having larger initial trim, ⑩ 10th cluster containing hull forms having smaller initial trim, ⑨ 9th cluster containing hull forms having higher chine-height, and ⑪ 11th cluster containing hull forms having lower chine-height.

Each hull form is restricted by its cluster until the minimum resistance hull form is obtained by SUMT method.

The obtained hull form is discussed by hull form's five elements.

The selected initial hull forms' numbers are No. 32, 68, 6, 56, 50 and 63. The obtained hull forms' characteristics are as follows. ⑥ hull form of 6th cluster is changed to have higher keel-high at Ord. 2 than that of initial model. ① 1st cluster, ⑩ 10th cluster and ⑨ 9th cluster are changed to have higher keel-high at Ord. 0, and higher keel-high and chine-height

Fig. 2. Relation between $C_{t3.5}$ and $\Delta\theta_{2.5}$

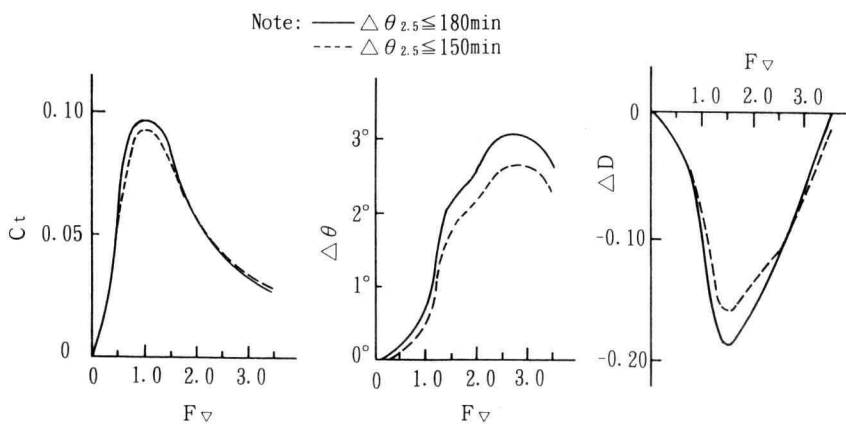
at Ord. 2.

Similar calculations for all other clusters have been done.

(2) Hull form obtained under all four conditions

In Fig. 2, $C_{t3.5}$ and $\Delta\theta_{2.5}$ relations are shown, where the models' mean value is expressed by mark "x" having $\Delta\theta_{2.5}=139$ min. and $C_{t3.5}=0.0339$.

From the 1st through 78th test models, $C_{t3.5}$ values have the general trend of taking higher values than the values which are obtained by the optimization calculation. Each curve that is made by the optimization calculations has decreasing tendency. Each optimization calculation is executed to get the minimum $C_{t3.5}$ hull form under keeping hull form's

Fig. 3. Relation among C_t , $\Delta\theta$ and ΔD

characteristics, and successively controlled $\Delta\theta_{2.5}=270, 240, 180$ min. etc.. The right edges of the curves show $C_{t3.5}$ values of the previous (1) step.

Under the controlled $\Delta\theta_{2.5}$, ⑥ 6th cluster hull form's resistance performance is shown in Fig. 3. The resistance performance for the controlled maximum trim angle change less than 180 min. is expressed by solid line, while one less than 150 min. by dotted line. By F_r and $\Delta\theta$ curves in Fig. 3 maximum trim angle changes show their own values for $F_r \geq 2.5$. The former initial trim angle $\theta = -52$ min. compared with the later one -58 min., where θ is an angle between waterline at rest and keel line from stations 5 (midship) to 10 (stern), taking positive when bow up. ΔD is nondimensional draft change at stern divided by half width b , taking positive for decreasing draft. The minimum resistance hull forms having decreasing controlled maximum trim angle changes such as 270, 240, 180 min. etc. become smaller in displacement volume, longer in total length, higher in cross point of chine line with keel line at bow, and higher in chine line. The mean value of total resistance coefficient's increment becomes 0.004/deg.

Conclusions

Obtained results are as follows.

(1) Expressing clusters on two dimensional plane of principal component axes, we try to visualize the mutual relations among test models. We have succeeded in decreasing loss of informations until finding one-to-one correspondence between a model and its characteristics. Hull form's five elements, which are useful rating scales to hull form, have been found by factor analyses.

(2) We propose the method how to determine the dimensions of the minimum resistance hull form. The object of this present paper is to restrict maximum trim angle change. Under successive decrease in maximum trim angle change, hull forms become smaller in displacement volume, longer in total length, higher in cross point of chine line with keel line at bow and higher in chine line. The mean value of total resistance coefficient's increment becomes 0.004/deg.

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