Jurnal Teknologi, bil. 24, Disember 1994 hlm. 23 – 43

COMPUTER AIDED RESISTANCE PREDICTION OF HIGH SPEED PLANING HULL FORMS

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Abstract. Planing crafts have been the traditional solution to high speed at sea. However, the limitations on high speed planing hull forms in a seaway have led to a tremendous amount of work currently being carried out on hydrofoils, catamarans and hybrid crafts. Despite these facts, the warship, commercial and pleasure markets still show demands for planing crafts and many new designs appear every year. The objective of this paper is to develop a computational procedure for predicting the total resistance of hard chine planing hull forms, prior to model testing. The computer prediction is later validated with existing experimental results.

1 INTRODUCTION

A planing craft is designed to develop dynamic lift on its bottom when at speed, so that it is more or less lifted up on top of the water, greatly reducing skin friction and wave making resistance. At Froude Number (with respect to wetted beam) larger than 1.5, a well designed planing craft should develop dynamic lift forces which will result in a significant rise of the centre of gravity, positive trim, emergence of the bow so that the wetted keel length is less than the waterline length, and the separation of flow occurs at the hard chine and transom.

As in other type of ship design studies, the prediction of powering for the planing craft is crucial. Insufficient power will unable the vessel to be lifted at the required speed, while excessive power will not only increase the building and maintenance costs but also reduces the deadweight of the craft.

Model experiments are a reliable method to predict the various aspects of ship performance before the ship is built. However, in view of the cost and amount of time involved, the amount of model testing in the early stages of design is usually restricted unless important innovations are involved in the design. The development of powerful computers has made it possible to construct computer models that evaluate the performance of the ship to be design.

This paper postulates the algorithm involves in predicting the total resistance of the bare hull of a planing craft. The results obtained from the computer model is then validated with existing experimental data.

2 ESTIMATION OF FORCES AND MOMENTS

For a hard chine hull, the independent variables which affect the values of the vertical lift force F_v, the skin friction F_s, and the location of the hydrodynamic centre l_H are the speed,

Typeset by $\mathcal{A}\mathcal{M}\mathcal{S}$-TEX the angle of trim, the deadrise angle, the mean wetted length, the mean wetted beam, gravity, density of water and the kinematic viscosity. Hence the vertical lift force can be written as (see Nomenclature for meaning of symbol)

$$\frac{F_v}{0.5\rho_w V^2 l_w^2} = \text{function}\left\{\alpha, \beta, \frac{b_w}{l_w}, \frac{V}{(gl_w)^{0.5}}, \frac{\rho_w V l_w}{\mu_w}\right\}$$

Since the flow about a practical hull is extremely complicated, reliance is placed on accurate experimental data. Unfortunately, the form in which the functional relationship is expressed contains the unknown wetted length on both sides of the expression. However, as Murray [1] and et al have argued that it is the wetted beam that is the important parameter (since it varies little with speed) and not the wetted length. Thus the above equation can be rearranged as follows:

$$C_v = \frac{F_v}{0.5\rho_w V^2 b_w^2} = \text{function}\left\{\alpha, \beta, \frac{b_w}{l_w}, \frac{V}{(gb_w)^{0.5}}\right\}$$

The *Reynold Number* is not included as experiments have shown that it has a negligible effect on the vertical force coefficient, C_v. Since β and $V/(gb_w)^{0.5}$ are both known at the preliminary design stage, the equation shows that C_v depends on the two unknowns α and l_w.

Savitsky in [3] developed an equation which relates the lift coefficient of a flat plate (C_{v_o}) to that of a plate of constant deadrise β, follows :

$$C_v = C_o - 0.0065\beta(C_{v_o})^{0.6}$$

where

$$C_v = \alpha^{1.1}\{0.0120\lambda^{0.5} + 0.0095\lambda^2(F_r)^{-2}\} \qquad \text{with } \lambda = \frac{b_w}{l_w}$$

The above empirical formula is applicable for $(0.60 < F_r < 13)$, $(2 < \alpha < 15)$ and λ greater than 4.

The coefficient of friction for wetted surface is assumed to be equal to C_f for the corresponding flat plank at a given *Reynold Number*, and an additional allowance of 0.0004 is then included for differences in roughness, curvature and corner interactions. Thus,

$$C_f = \frac{F_s}{0.5\rho_w V^2 s_w} \qquad \text{with } s_w = l_w b_w \sec\beta$$

Experimental data has shown that the location of the hydrodynamic centre H is independent of both *Reynold Number* and *Froude Number*. Hence,

$$\frac{l_H}{b_w} = \text{function}\{\alpha, \beta, \frac{b_w}{l_w}, \}$$

The hydrodynamic and static forces acting on a planing hull is shown in Figure 1. In a state of equilibrium, the vertical lift force must be equal to the weight as shown in Figure 2. Thus for a steady motion, the net moment of forces about G is given

$$F_h\{(I_G - I_X)\cos\psi + z_H \sin\psi\} - Tz_T - F_p - F_p\{(I_H - I_G)\cos\phi - z_H \sin\phi\} + F_s z_H.$$

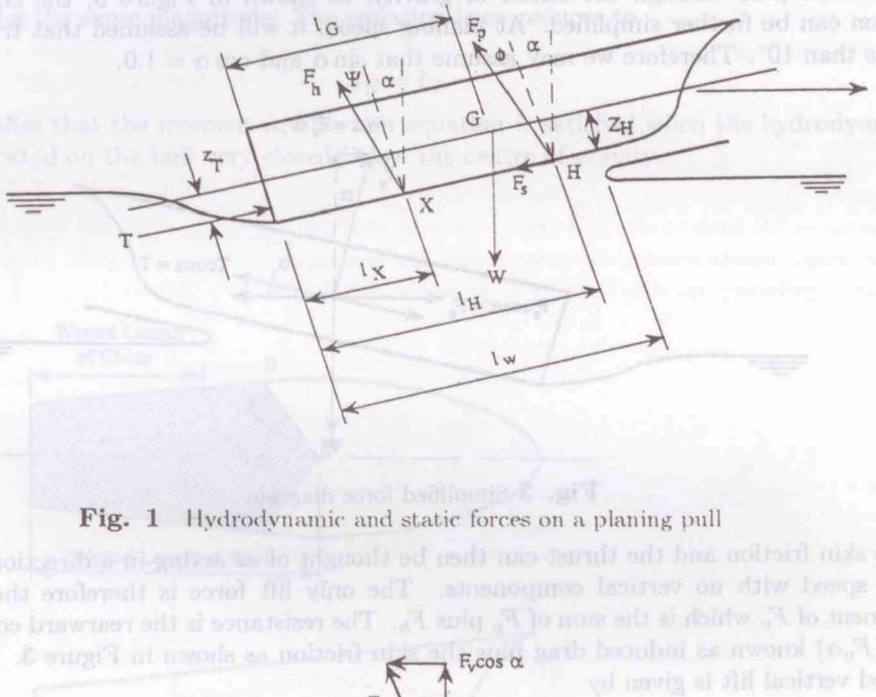

Fig. 1 Hydrodynamic and static forces on a planing pull

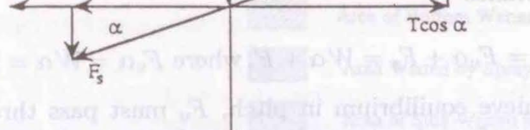

Fig. 2 Free body diagram

while for the euilibrium of forces

$$W - F_h \cos(\alpha + \psi) - F_p \cos(\alpha + \phi) + F_s \sin\alpha - T \sin\alpha = 0$$

The required vertical lift is given by

$$W = F_v \cos\alpha + T \sin\alpha - F_s \sin\alpha \qquad \text{where } F_v = F_p \cos\phi + F_h \cos\psi$$

and the total resistance is given by

$$R_T = T \cos\alpha = F_v \sin\alpha + F_s \cos\alpha$$

By assuming the simple planing case where the thrust axis and the viscous force vector coincide and pass through the centre of gravity, as shown in Figure 3, the equilibrium equation can be further simplified. At planing speed, it will be assumed that trim angles are less than 10°. Therefore we may assume that $\sin\alpha$ and $\cos\alpha = 1.0$.

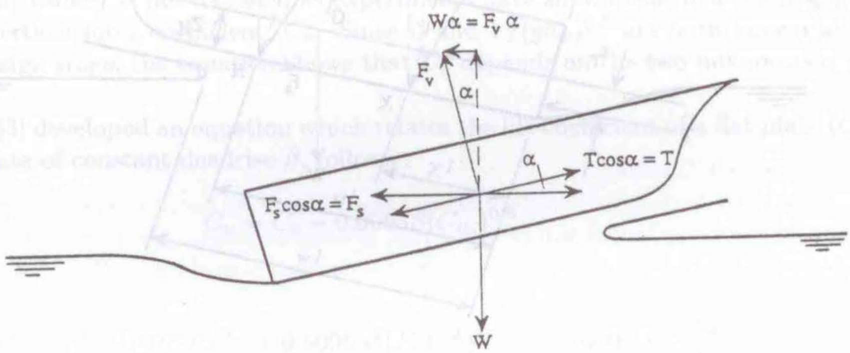

Fig. 3 Simplified force diagram

The skin friction and the thrust can then be thought of as acting in a direction parallel to the speed with no vertical components. The only lift force is therefore the vertical component of F_v which is the sum of F_p plus F_h. The resistance is the rearward component of F_v $(F_v\alpha)$ known as induced drag plus the skin friction as shown in Figure 3. Thus the required vertical lift is given by

$$W = F_v = F_p + F_h$$

and the total resistance

$$R_T = F_v\alpha + F_s = W\alpha + F_s \text{ where } F_v\alpha = W\alpha = \text{induced drag}$$

In order to achieve equilibrium in pitch, F_v must pass through the centre of gravity. Hence, the buoyancy force is assumed to have the same centre of application as the hydrodynamic force, that is F_v is acting at $l_X = l_H$. From the equilibrium of moments,

$$F_v\{(l_H - l_G)\cos\phi - z_H \sin\phi\} = F_s z_H - T z_p$$

and

$$T \cos \alpha = F_v \sin(\alpha + \phi) + F_s \cos \alpha$$

Hence,

$$F_v\{(l_H - l_G)\cos\phi - z_H \sin\phi\} = F_s z_H - \left\{\frac{F_v \sin(\alpha+\phi)}{\cos\alpha} + F_s\right\} z_p$$

Rearranging the above equation, one obtains

$$(l_H - l_G) = (z_H - z_T)\left\{\left(\frac{F_v}{F_p}\right)\sec\phi + \tan\phi\right\} - z_p \tan\alpha$$

As ϕ and α are both small it is reasonable to assume that z_H and z_p are both small and nearly having the same magnitude. The equation then reduces to

$$l_H = l_G$$

This implies that the moment equilibrium equation is satisfied when the hydrodynamic centre is located on the hull very closed below the centre of gravity.

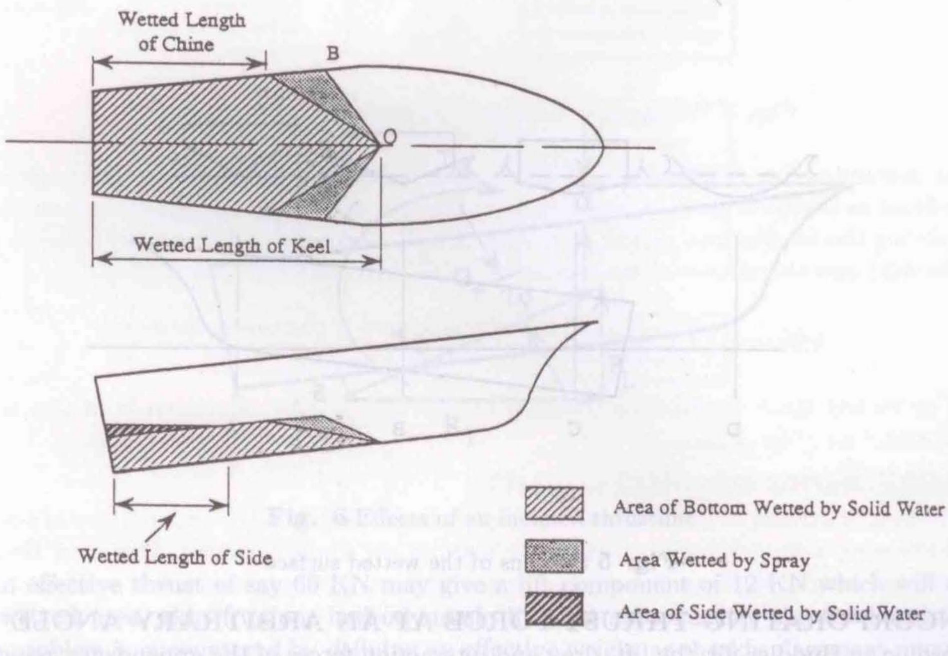

Fig. 4 Geometry of the wetted surface

3 GEOMETRY OF THE HULL

Since most planing hulls do not have prismatic forms, it is important to define an 'effective' beam and deadrise angle to be used with the prismatic planing equations. Blount and Fox in [5] have made resistance predictions for a number of existing hull forms for which the model data existed. Their purpose have been to identify an effective beam and the deadrise angle which will result in the best analytical predictions in the planing speed range. The comparisons made indicate that the maximum chine beam and the deadrise at mid-chine length give the best predictions at high speeds. Regarding 'effective' angle of trim for a hull with longitudinal curvature of the wetted surface, Savitsky in [3] suggests that the trim angle should be taken as the average of the keel and chine buttocks line in the stagnation area of the hull.

The length of the wetted plan profile of the planing hull varies across the breadth, thus a mean wetted length defined as the average of the keel and chine lengths measured from the transom to the intersection with the spray-root line is adopted in this study. The wetted surface is obtained from

$$s_w = l_w b_w \sec\beta$$

with aspect ratio defined as b_w/l_w.

Figure 5 illustrates how a planing hull slides through the water. The steep waves shown in C sometimes fell back to the hull and cause side wetting. The degree of side wetting depends on the speed, displacement, deadrise angle and the aspect ratio of the hull. However, since it is not significant, no side wetting is assumed in this study.

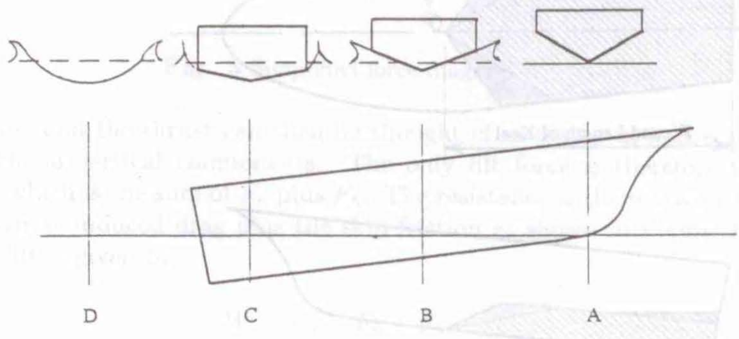

Fig. 5 Sections of the wetted surface

4 INCORPORATING THRUST FORCE AT AN ARBITRARY ANGLE

According to Huddler [6], the lift, drag and interaction forces of the appendages associated with the propulsion and control systems are secondary forces of the propellers.

The forces which arise from the propeller are those generated by the propeller itself which are transmitted to the hull through the shafting and struts, and the pressure forces induced on the planing surface from the propeller loading results in a suction force on the bottom of the hull on the upstream or forward side of the propeller as well as a pressure force on the downstream or after side of the propeller. The former force can be calculated by using results in Gutche [15] from an investigation of the steady forces generated by a propeller in inclined flow. Hough [16] has presented an expression for the induced velocity components of a free propeller which can be used to determine the pressure forces induced by the propeller upon the hull.

Since the primary objective of this study is to evaluate the total resistance of the bare hull and to give an indication of the effective thrust required, it is desirable to avoid the calculation of the induced propeller forces and normal forces. By assuming that both forces cancel each other, the inclined propeller thrust is the remaining force that affects the performance of the planing craft. This means that the suction force upstream is equal and opposite to the pressure force downstream and the normal crossflow component of the propeller disk due to the inclined flow. The trimming moment due to the induced forces may give a slight bow down moment, but since it is small and also favourable in most circumstances, it is prudent to assume it to be zero.

Since it is quite common to have a propeller shaft inclination in the order of 10° to 12°, and bearing in mind that a large thrust force is required in the planing speed range, it is desirable to investigate what effect this has on the performance. The lift component of the thrust (propeller lift), and the thrustline moment, are going to affect the angle of trim and the wetted area as shown in Figure 6.

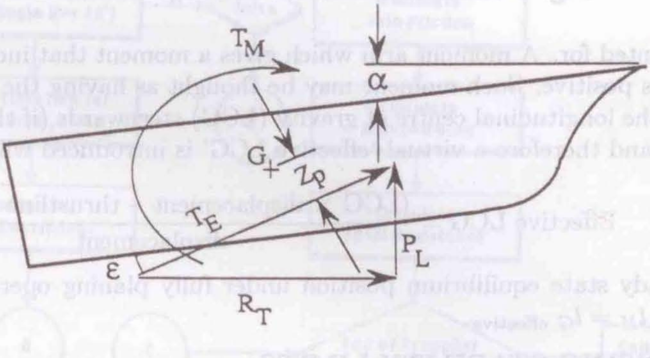

Fig. 6 Effects of an inclined thrustline

An effective thrust of say 60 KN may give a lift component of 12 KN which will affect the wetted area, skin friction, hydrodynamic lift and subsequently the total resistance. This problem is encountered by defining an effective weight as the (displacement minus the propeller lift) and utilising this effective weight in the evaluation of the hydrodynamic lift and skin friction.

If the thrustline does not pass through the centre of gravity, the thrustline moment has

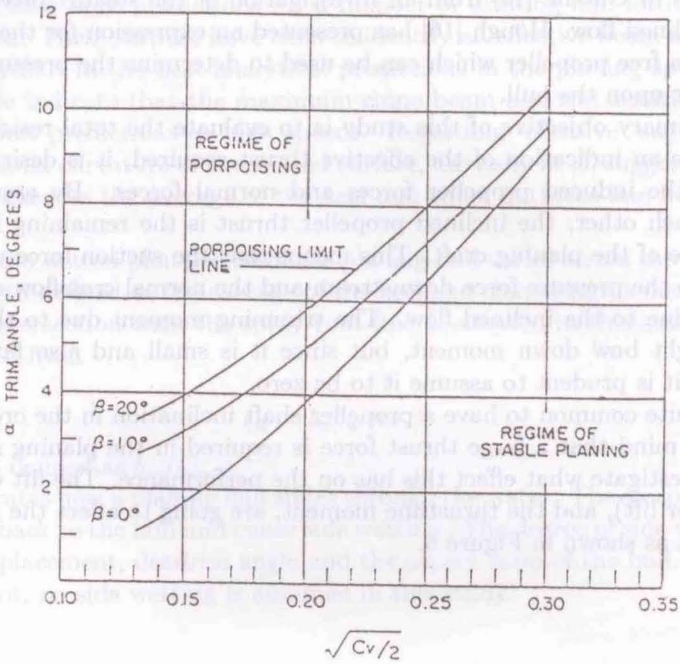

Fig. 7 Relationship between trim angle and lift coefficient [8]

to be accounted for. A moment arm which gives a moment that increases the angle of trim is defined as positive. Such moment may be thought as having the same effect on the trim as moving the longitudinal centre of gravity (LCG) sternwards (if thrustline is below centre of gravity) and therefore a virtual 'effective LCG' is introduced where

$$\text{Effective LCG} = \frac{(\text{LCG} \times \text{displacement} - \text{thrustline moment})}{\text{displacement}}$$

The steady state equilibrium position under fully planing operation is at the angle of trim where $l_H = l_{G\ \text{effective}}$.

5 PORPOISING STABILITY LIMITS

Porpoising is defined as the combined oscillations of a craft in pitch and in heave of sustained or increasing amplitude occurring while planing on smooth water. Day and Haag [18] developed graphs showing the relationships between trim angle and lift coefficient which defines the inception of porpoising. These relationships are shown graphically in Figure 7 for 0°, 10° and 20° deadrise prismatic planing surfaces. The combination of the angle of trim and lift coefficient which fall below the limit curves indicate stable operation, while those above the line indicate the existence of porpoising.

6 COMPUTER FLOWCHART

The complete computational procedure is given in Figure 8. The input data required to run the computer program are as follows:

a. length, wetted beam, displacement and speed of vessel,

b. deadrise angle and shaft inclination angle,

c. mean length of skeg and surface area of skeg,

d. distance of shaft from vertical centre of gravity and the location of vessel's longitunal centre of gravity, and

e. density and kinematic viscosity of water

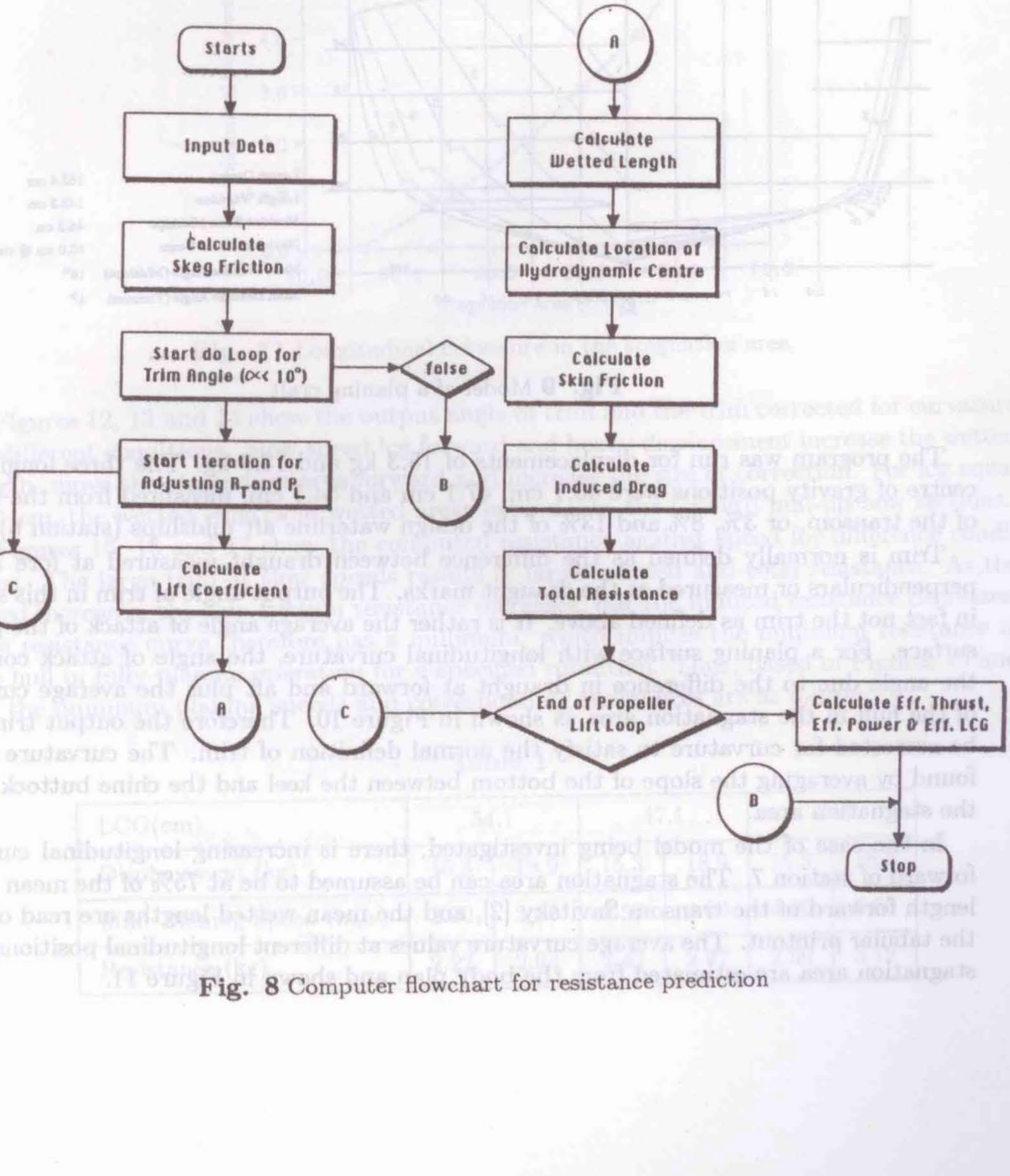

Fig. 8 Computer flowchart for resistance prediction

Before running the program, the input data should be checked against the limitations on Savitsky's equation given earlier.

7 EXAMPLE OF EXECUTION

A 1 : 13 scale model of a 21.5 m patrol craft is used to validate the results obtain from the computer program. The main dimension and body plan of the craft is given in Figure 9. The hull form is a combination of round bilge and hard chine together with sprays deflecting rails. Even though the program develop is to be used for hard chine, prismatic like, hull form, the model is assumed suitable since it have hard chines which defines the wetted beam.

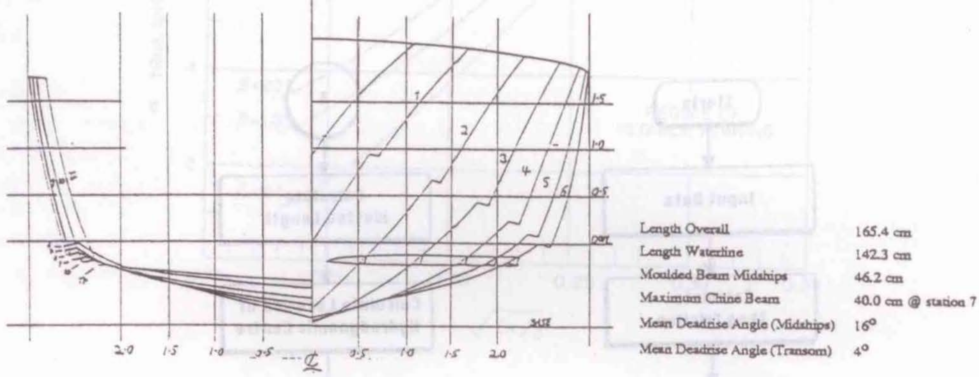

Fig. 9 Model of a planing craft

The program was run for displacements of 15.3 kg and 18.9 kg. The three longitudinal centre of gravity positions were 40.1 cm, 47.1 cm and 54.1 cm, measured from the bottom of the transom, or 3%, 8% and 13% of the design waterline aft midships (station 6).

Trim is normally defined as the difference between draught measured at fore and aft perpendiculars or measured at the draught marks. The output angle of trim in this study is in fact not the trim as defined above. It is rather the average angle of attack of the planing surface. For a planing surface with longitudinal curvature, the angle of attack consist of the angle due to the difference in draught at forward and aft plus the average curvature of the hull in the stagnation area as shown in Figure 10. Therefore the output trim must be corrected for curvature to satisfy the normal definition of trim. The curvature can be found by averaging the slope of the bottom between the keel and the chine buttock line in the stagnation area.

In the case of the model being investigated, there is increasing longitudinal curvature forward of station 7. The stagnation area can be assumed to be at 75% of the mean wetted length forward of the transom Savitsky [2], and the mean wetted lengths are read off from the tabular printout. The average curvature values at different longitudinal positions of the stagnation area are estimated from the body plan and shown in Figure 11.

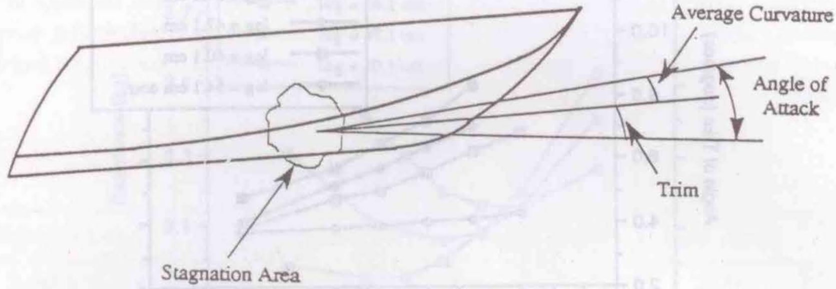

Fig. 10 Definition for angle of attack

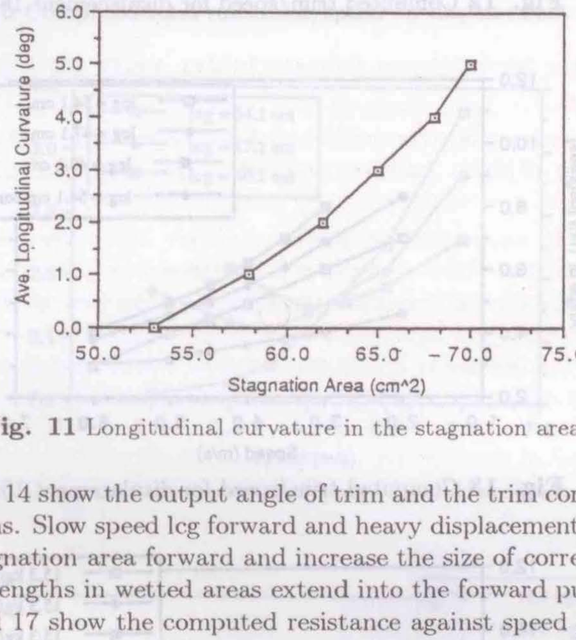

Fig. 11 Longitudinal curvature in the stagnation area

Figures 12, 13 and 14 show the output angle of trim and the trim corrected for curvature for different conditions. Slow speed lcg forward and heavy displacement increase the wetted length, move the stagnation area forward and increase the size of correction. For lcg equal 54.1 cm, the wetted lengths in wetted areas extend into the forward pull-up bow sections.

Figures 15, 16 and 17 show the computed resistance against speed for difference conditions. The large trim at slow speeds results in large induced and total resistance. As the speed increases, the skin friction resistance increases, but the induced resistance decreases. The resistance curve therefore has a minimum, which implies the minimum resistance of the hull in fully planing operation for a specified condition. Thus, based of Figures 15 and 16, the minimum planing speeds and corresponding resistances are as follows:

Table 1

LCG(cm)	54.1		47.1		40.1	
Displacement (kg)	15.3	18.9	15.3	18.9	15.3	18.9
Min. Planing Speed (m/s)	2.00	3.50	3.50	4.00	4.00	5.00
Resistance (kg)	2.22	2.94	2.42	2.97	2.50	3.12

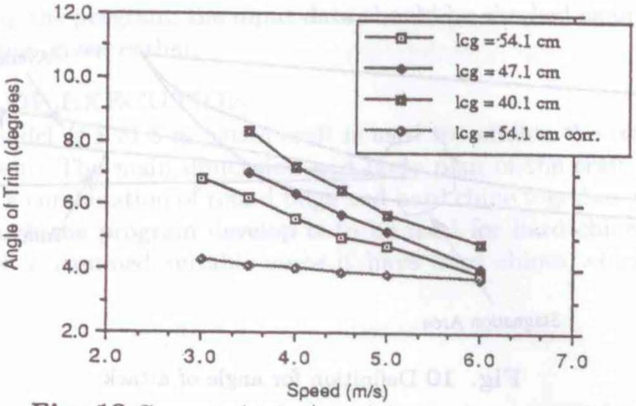

Fig. 12 Computed trim/speed for displacement 18.9 kg

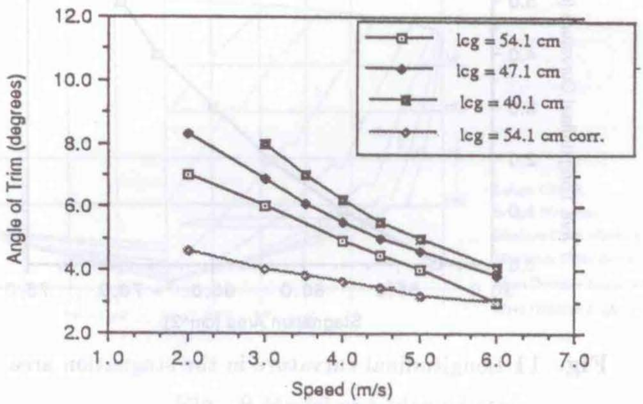

Fig. 13 Computed trim/speed for displacement 15.3 kg

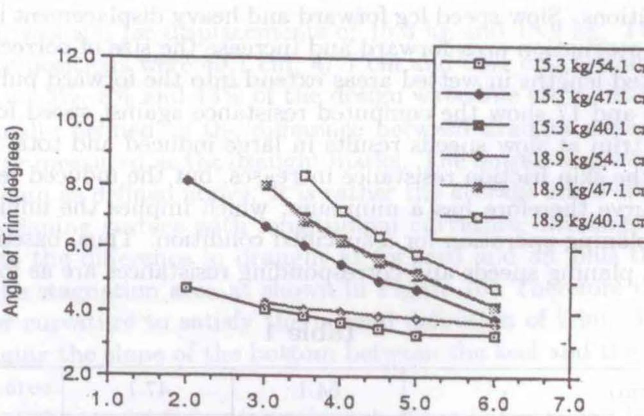

Fig. 14 Trim corrected for hull curvature/speed

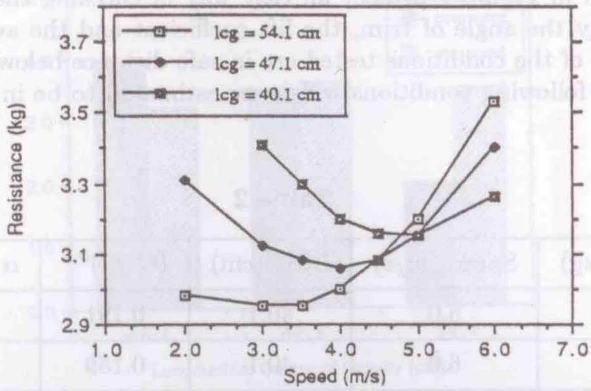

Fig. 15 Computed total resistance/speed for displacement 18.9 kg

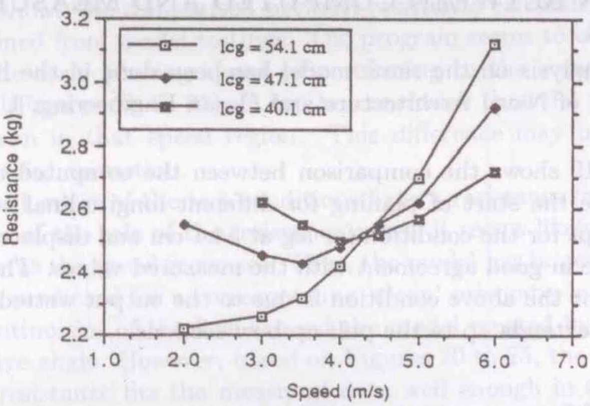

Fig. 16 Computed total resistance/speed for displacement 15.3 kg

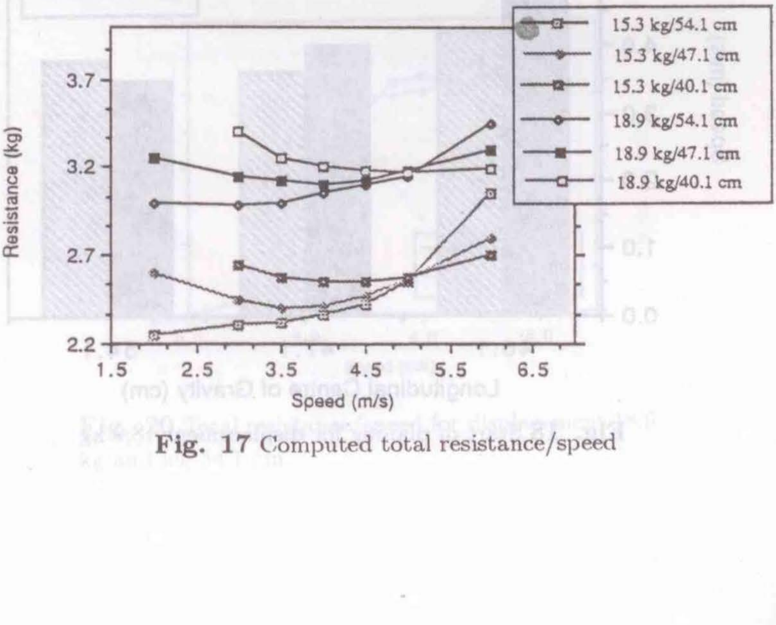

Fig. 17 Computed total resistance/speed

The graph given in Figure 7 present an easy way of checking the porpoising stability of the design. Only the angle of trim, the lift coefficient and the average deadrise angle are required. Most of the conditions tested are in safe distance below the porpoising limit line except for the following conditions which are estimated to be in the border region of porpoising :

Table 2

Disp. (kg)	Speed (m/s)	LCG (cm)	$(C_v/2)^{0.5}$	α (degrees)
15.3	5.0	40.1	0.191	4.95
15.3	6.0	40.1	0.159	4.05

8 COMPARISON BETWEEN COMPUTED AND MEASURED RESISTANCE

An experimental analysis on the same model has been done in the Hydrodynamic Laboratory, Department of Naval Architecture and Ocean Engineering, University of Glasgow [9].

Figures 18 and 19 shows the comparison between the computed and measured values for the speed where the start of planing for different longitudinal centre of gravity and displacement. Except for the condition for lcg at 54.1 cm and displacement at 15.3 kg, the computed values are in good agreement with the measured values. The underestimation of the planing speed for the above condition is due to the output wetted length predicted by the program which extends up to the pull-up bow sections.

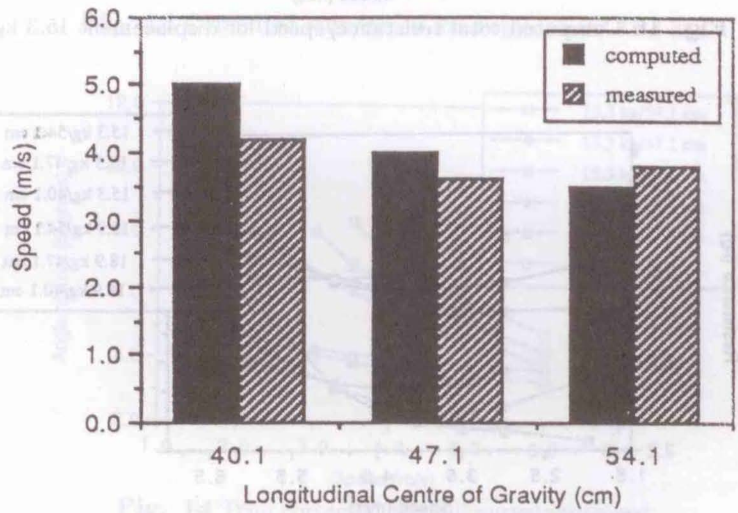

Fig. 18 Start of planing for displacement 18.9 kg

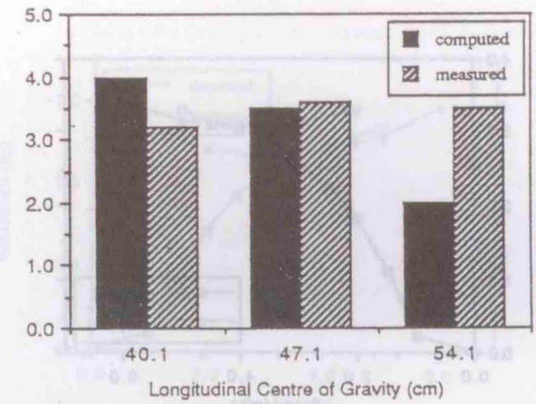

Fig. 19 Start of planing for displacement 15.3 kg

Figures 20 to 25 shows the comparison between resistance calculated from the program and the values obtained from model testings. The program seems to overestimates slightly the resistance for the early planing speed. By referring to the comparison of measured and computed trim (Figures 26 to 31), it can be concluded that the program pronouncly overestimates the trim in that speed region. This difference may be partly due to the uncertainties in the trim correction.

At maximum speed, most of the test conditions have a resistance larger than predicted. By judging the slope of the tale of the resistance curve, it seems likely that this difference will continue to grow as the speed increases. Thus, the model has larger resistance at higher speeds than what is predicted for a corresponding 'clean' prismatic hull. This results may be due to the discontinuities of the flow around the model created by sprayrails and hard chines with a negative angle. However, based on Figures 20 to 25, the differences are small and the computed resistance fits the measured data well enough in terms of preliminary design perspective.

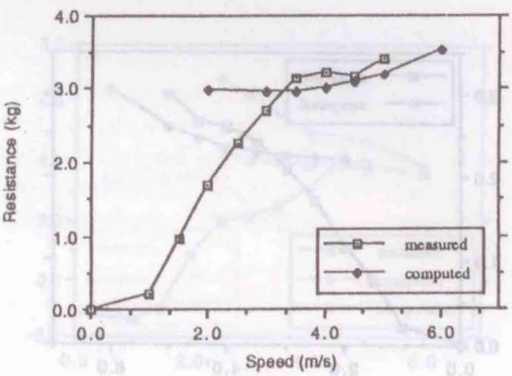

Fig. 20 Total resistance/speed for displacement 18.9 kg and lcg 54.1 cm

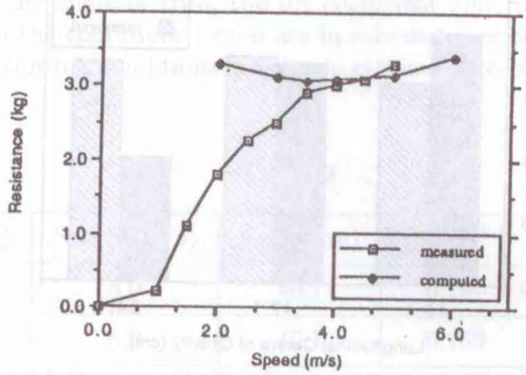

Fig. 21 Total resistance/speed for displacement 18.9 kg and leg 47.1 cm

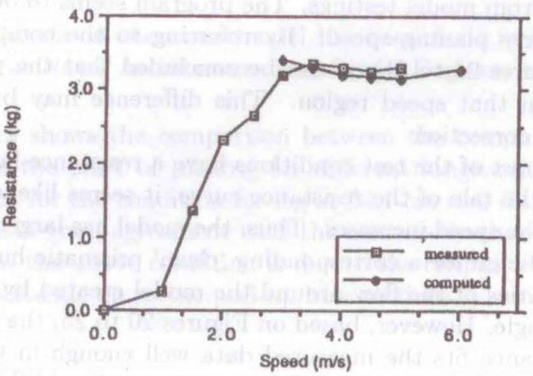

Fig. 22 Total resistance/speed for displacement 18.9 kg and leg 40.1 cm

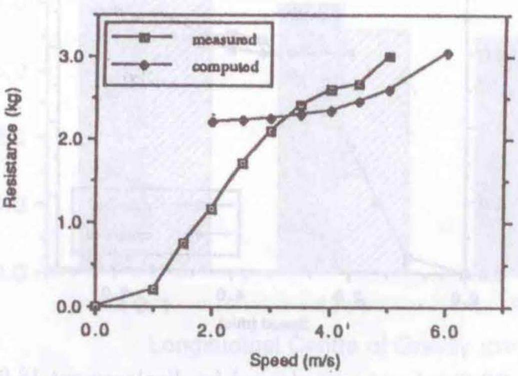

Fig. 23 Total resistance/speed for displacement 18.9 kg and leg 54.1 cm

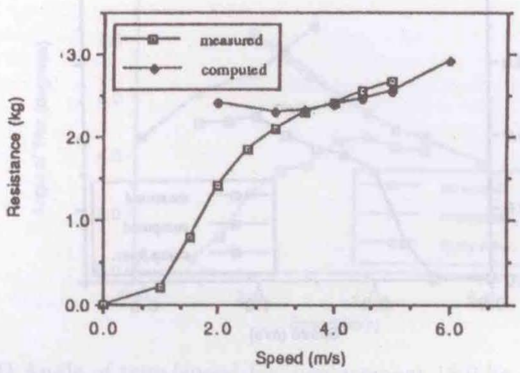

Fig. 24 Total resistance/speed for displacement 18.9 kg and leg 47.1 cm

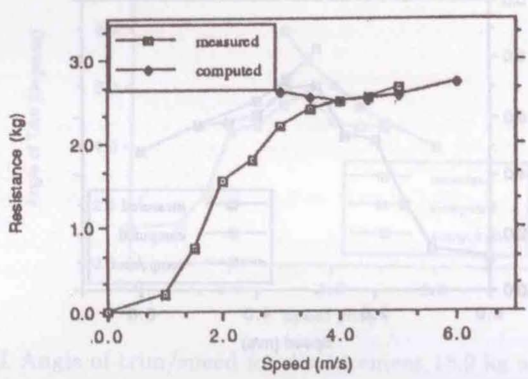

Fig. 25 Total resistance/speed for displacement 18.9 kg and leg 40.1 cm

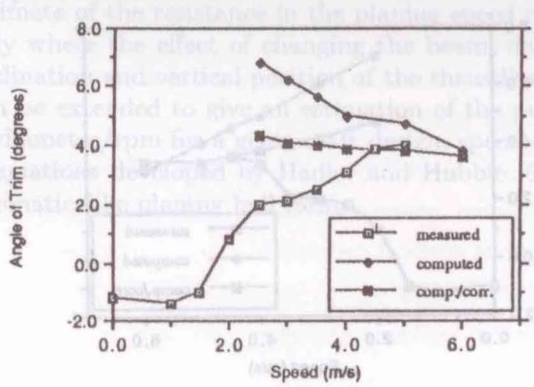

Fig. 26 Angle of trim/speed displacement 18.9 kg and leg 54.1 cm

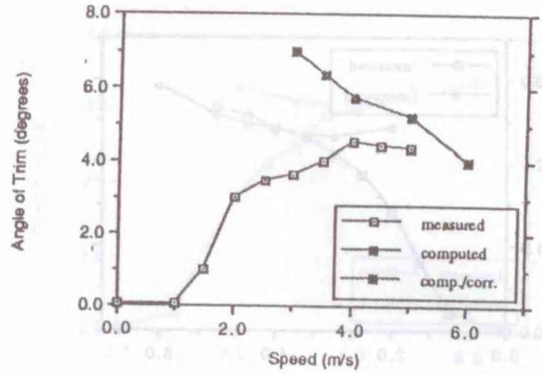

Fig. 27 Angle of trim/speed for displacement 18.9 kg and leg 47.1 cm

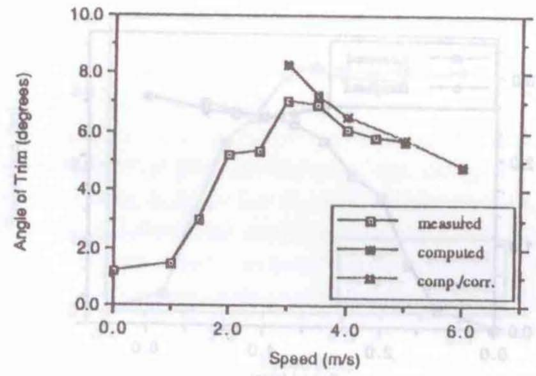

Fig. 28 Angle of trim/speed for displacement 18.9 kg and leg 40.1 cm

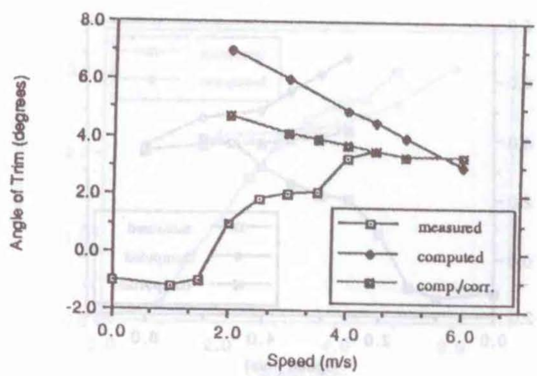

Fig. 29 Angle of trim/speed for displacement 18.9 kg and leg 54.1 cm

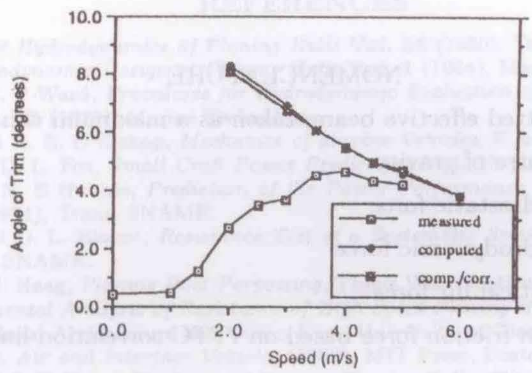

Fig. 30 Angle of trim/speed for displacement 18.9 kg and leg 47.1 cm

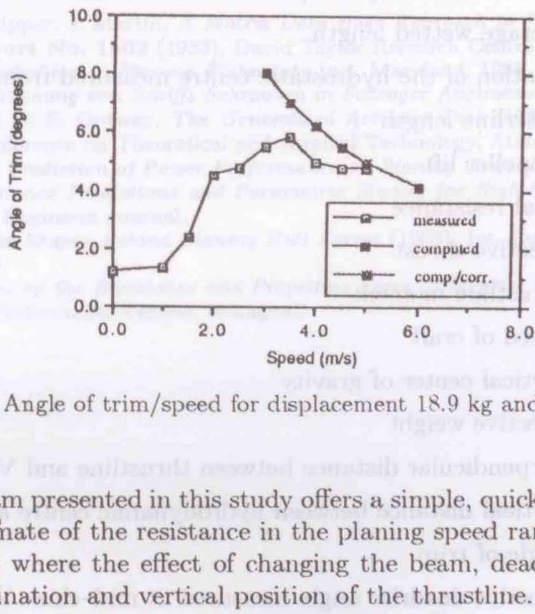

Fig. 31 Angle of trim/speed for displacement 18.9 kg and leg 40.1 cm

9 CONCLUSION

The computer program presented in this study offers a simple, quick and quite accurate way to obtain a first estimate of the resistance in the planing speed range. It can also be used for parametric study where the effect of changing the beam, deadrise, leg, displacement, size of skeg, and inclination and vertical position of the thrustline.

The program can be extended to give an estimation of the power requirement and the optimum propeller diameter/rpm for a given craft design, speed and propulsion system by incorporating the equations developed by Hadler and Hubble [6] for prediction of power performance for prismatic–like planing hull forms.

NOMENCLATURE

b_w	wetted effective beam, taken as a maximum chine beam
CG (or G)	centre of gravity
F_h	hydrostatic force
F_p	hydrodynamic force
F_v	vertical lift force
F_s	skin friction force based on ITTC correlation line
g	gravity
l_G	longitudinal centre of gravity measured from the stern
l_H	location of the hydrodynamic centre measured from the stern
l_w	average wetted length
l_x	location of the hydrostatic centre measured from the stern
l_{WL}	waterline length
P_L	propeller lift
R_T	total resistance
T	effective thrust
T_M	thrustline moment
V	speed of craft
VCG	vertical center of gravity
W	effective weight
z_p	perpendicular distance between thrustline and VCG
z_H	vertical distance between hydrodynamic centre and VCG
α	angle of trim
β	effective deadrise angle measured at mid–chine length
ε	propeller shaft inclination
Φ, ψ	longitudinal curvature of hull at H and X respectively
	(H denotes centre of hydrodynamic pressure and X denotes
	(centre of statical pressure)
ρ_w	density of water
μ_w	kinematic viscosity of water

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