Second International Conference on Stability of Ships and Ocean Vehicles, Tokyo, Oct.1982

SII-2b

A SIMULATION STUDY ON SWAY-ROLL-YAW COUPLED INSTABILITY OF SEMI-DISPLACEMENT TYPE HIGH SPEED CRAFT

EIICHI BABA, SHIGERU ASAI AND NAOJI TOKI

Mitsubishi Heavy Industries, Ltd.

Japan

ABSTRACT

To investigate into the roll induced instability of semi-displacement type high speed craft, simulation studies were carried out for sway-roll-yaw coupled motions. Hydrodynamic coefficients for the simulation studies were obtained by means of captive model test for a round bilge type hull form with and without spray strips, and for a hard chine type hull form. It was found that metacentric height GM rather than the difference in hull forms has a major effect on the roll induced instability of semi-displacement craft at high forward speeds. It was also found that course stability is improved by spray strips which show an effect to raise the vertical position of acting point of sway force.

NOMENCLATURE

[Physical constant]

g	Acceleration of gravity	(m/sec^2)
ρ	Density of water	$(kg.sec^2/m^4)$

[Hull]

L	Length on load waterline	(m)
B	Breadth	(m)
d	Draft at midship	(m)
x_G	x co-ordinate of center of gravity G	(m)
z_G	z co-ordinate of G	(m)
KG	Height of G from keel line	(m)
Δa	Displacement of hull with appendages	(kg)
k_{xx}	Radius of gyration about x axis	(m)
k_{zz}	Radius of gyration about z axis	(m)
I_{xx}	Moment of inertia about x axis	$(kg.m.sec^2)$
I_{zz}	Moment of inertia about z axis	$(kg.m.sec^2)$

[Propeller]

D	Diameter	(m)
P	Pitch	(m)

[Rudder]

x_R	x co-ordinate of rudder stock	(m)
z_R	z co-ordinate of mid point of rudder height	(m)
b	Breadth	(m)
h	Height	(m)
A_R	Rudder area $A_R = b \cdot h$	(m^2)
λ	Aspect ratio of rudder	$\lambda = h / b$

[Motion]

u	Velocity in x direction	(m/sec)
F_n	Froude number	$F_n = u/\sqrt{g.L}$
v	Sway velocity	(m/sec)
U	Advance speed	(m/sec)
U_s	Advance speed of full scale ship	(kn)
β	Drifting angle	(deg)
r	Yaw rate	(deg/sec)
ψ	Yaw angle	(deg)
φ	Heel angle, Roll angle	(deg)
n_P	Rate of propeller revolution	(rps)
δ	Rudder angle	(deg)

[Hydrodynamic characteristics]

X	Force in x direction	(kg)
Y	Sway force	(kg)
N	Yaw moment	(kg.m)
K	Heel moment, Roll moment	(kg.m)
R_f	Frictional resistance	(kg)
R_r	Residual resistance	(kg)
T	Propeller thrust	(kg)
t	Thrust deduction factor	
w	Effective wake fraction	

u_P	Inflow velocity toward propeller $u_P = (1 - w)u$	(m/sec)
m_x	Added mass in x direction	(kg.sec^2/m)
m_y	Added mass in y direction	(kg.sec^2/m)
J_{xx}	Added mass moment of inertia about x axis	(kg.m.sec^2)
J_{zz}	Added mass moment of inertia about z axis	(kg.m.sec^2)
x_Y	x co-ordinate of acting point of sway force Y	(m)
z_Y	z co-ordinate of acting point of sway force Y	(m)

1. INTRODUCTION

It is known that a high speed ship with relatively small metacentric height GM sometimes undergoes difficulty in keeping her course straight (Refs.1 to 3). This behaviour is explained in connection with hydrodynamical asymmetry of the underwater hull form due to roll and this phenomenon is called "roll induced instability".

In the case of high speed craft, the phenomenon is more critically related to the safety of operation. Therefore, studies have been made by several researchers so far, especially putting an emphasis on reduction of virtual transverse stability (Refs.4 to 7). However, detailed causes for the roll induced instability have not yet been fully explained, especially of high speed craft. In Nagasaki Experimental Tank, it has been also noticed that a semi-displacement type high speed craft has a heel angle possibly caused by the reduction of virtual GM during its resistance test at relatively high speed. For assuring the phenomenon, free-running model test was carried out. Typical examples of the test results are shown in Fig. 1, where marked port turning is observed for the condition of small GM even at zero helm. And this turning is associated with outward heel, i.e. starboard heel at port turning and port heel at starboard turning, either of which eventually invites capsizing.

Considering these situations, a basic investigation is made on the phenomenon by means of captive model test. And utilizing thus obtained hydrodynamic coefficients, simulation study is carried out on sway-roll-yaw coupled motions.

2. CAPTIVE MODEL TEST

2.1 Tested Models

Two types of semi-displacement type high speed craft model were used, i.e. a round bilge type (with and without spray strips) and a hard chine type. Principal particulars and body plans are shown in Table 1 and Fig. 2, respectively. Experiments were made in Nagasaki Experimental Tank, M.H.I. Taking operation conditions into account, speed of the model was varied in the range of Froude number F_n from 0.46 to 1.00 covering full scale speed ranging from 20 to 44 knots.

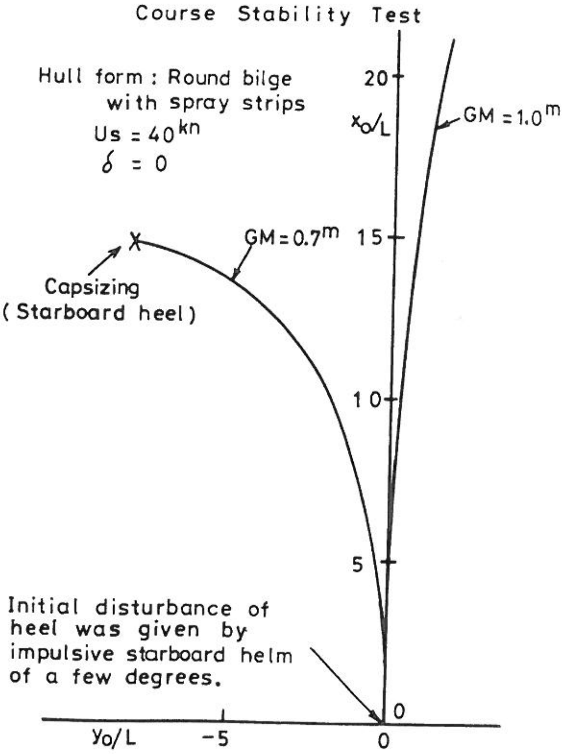

Fig. 1 Observed trajectories obtained photographically by use of the free-running model with a pinpoint flash-light

Table 1 Principal Particulars of the Hull Forms for Captive Model Tests and Simulation

Item \ Hull form	A (Round bilge with spray strips)	B (Hard chine)
Load condition	Design load	Design load
Scale ratio	1 / 14·3	1 / 14·3
L (m)	3·600	3·600
B (m)	0·503	0·566
d (m)	0·126	0·105
L / B	7·15	6·36
B / d	4·00	5·39
A_R / (L·d)	1 / 31·6	1 / 26·4

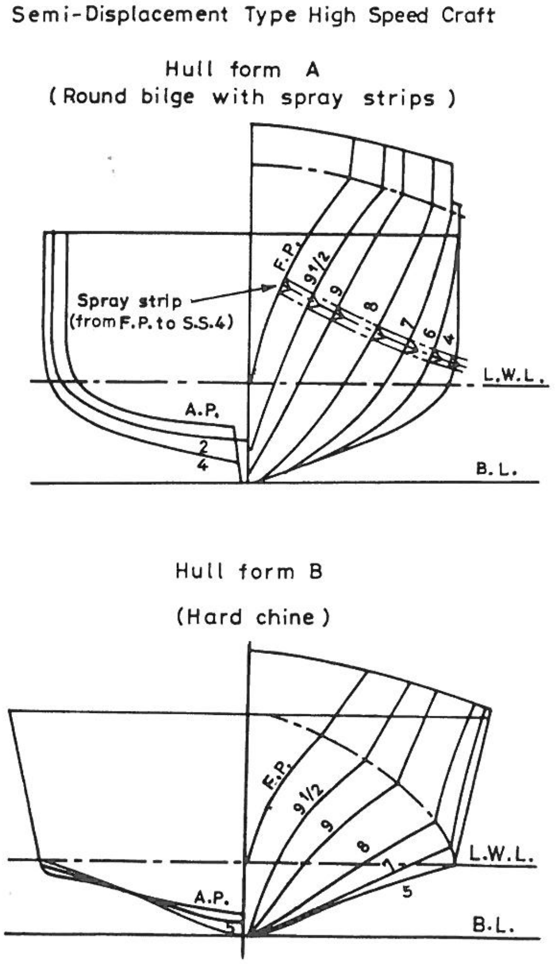

Fig. 2 Body plans of the hull forms for captive model tests and simulation

2.2 System of Measurement

Hydrodynamic forces and manoeuvring motions are defined in reference to the co-ordinate systems shown in Fig. 3. In the captive model tests, following hydrodynamic forces were measured, i.e. lateral forces acting on the fore and aft guides, vertical force acting on the gauge for heel moment, and rudder normal force. System of the measurement is shown in Fig. 4. In the heel free condition, heel moment was obtained from measured increase of heel angle and static GM, and in the heel restrained condition, it was obtained from measured vertical force acting on the gauge for heel moment.

2.3 Results of Captive Model Test

As the basic tests for steady manoeuvring characteristics, three kinds of captive model test were carried out. In these tests, sway force Y, yaw moment N, and others were obtained versus various heel angle, oblique tow angle, and rudder angle.

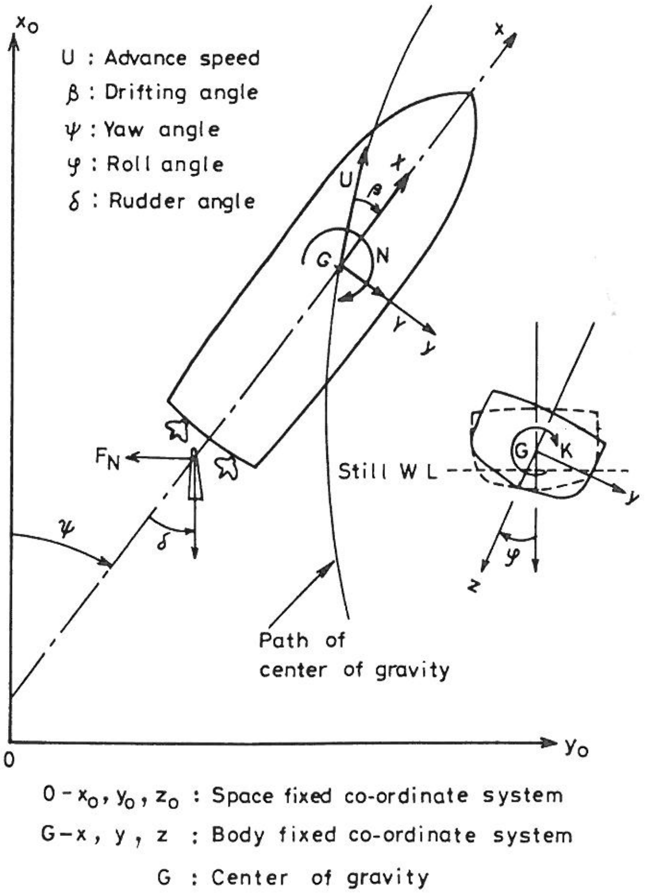

Fig. 3 System of co-ordinates and symbols

Y and N were non-dimensionalized by following definitions:

$$\left.\begin{aligned} Y' &= Y/(\ \tfrac{\rho}{2}\ L\ d\ U^2\ ) \\ N' &= N/(\ \tfrac{\rho}{2}\ L^2 d\ U^2\ ) \end{aligned}\right\} \qquad (1)$$

where U denotes advace speed.

[1] Heel Angle Test

Heel angle ϕ of the model in straignt course running was varied by transverse shift of a small ballast weight in the range of ϕ from -10 to 10 degrees. Results of the test are shown in Fig. 5, where derivative of Y' with respect to ϕ of the hull form A is similar to that of the hull form B, although slight difference is observed in derivatives of N' with respect to ϕ of the hull forms A and B. It is also found that Y' and N' obtained for the range of F_n from 0.90 to 1.00 show no substantial differences from the other results obtained for the range of F_n from 0.46 to 0.90.

[2] Oblique Towing Test

The model was towed obliquely to a straight course, and drifting angle β was

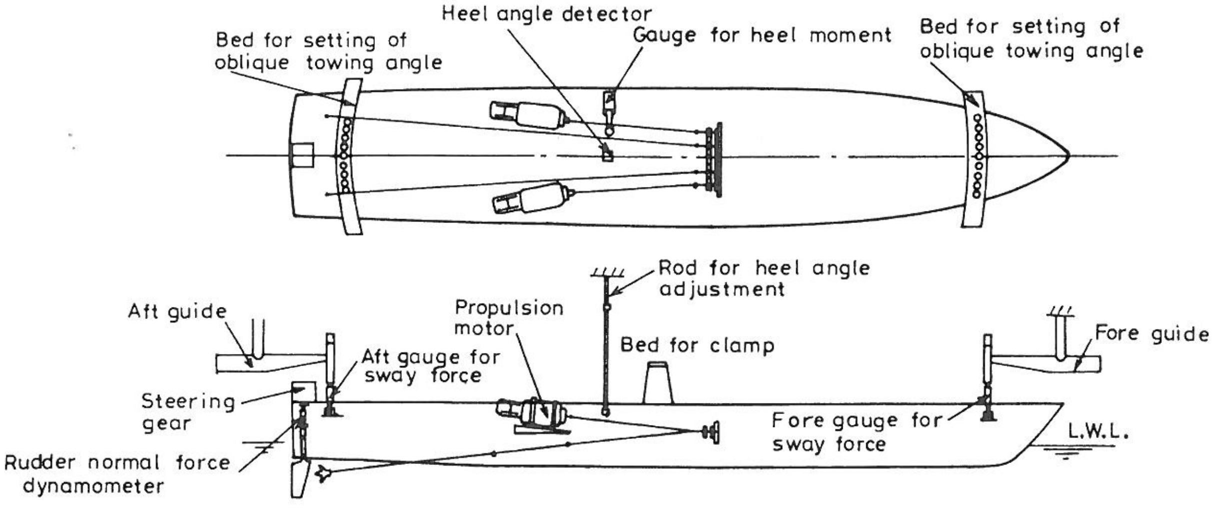

Fig. 4 System of measurement in captive model tests

varied in the range of β from -3 to 3 degrees. Analysis was made for β-component force Y(β) and moment N(β) by subtracting ϕ-component force Y(ϕ) and moment N(ϕ) from total force Y and moment N, respectively, where Y(ϕ) and N(ϕ) were obtained from the heel angle test results shown in Fig. 5. Results of the test are shown in Figs. 6 to 8. In Figs. 7 and 8, x and z co-ordinates of acting point of Y(β) are plotted respectively. Characteristics of both hull forms A and B are very similar to one another in these Figs. 6 to 8. From Fig. 8, it is found that acting points of Y(β) lie well close to the load waterline $z_{Y(\beta)} = 0$ within the range of β from -3 to 3 degrees. In Figs. 6 to 8, the results are also shown of the hull form B at which heel angle was restrained to zero. These results agree with the characteristics obtained from β-component force Y(β) and moment N(β) at the heel free condition. This fact indicates the possibility of linear superposition of β- and ϕ-component forces and moments, when the tested hull form runs in the vicinity of straight course with small heel angle.

[3] Rudder Angle Test

Rudder angle δ was varied in the range of δ from -7 to 7 degrees while the model was running in a straight course. Results of the test are shown in Fig. 9, where Y'_R and N'_R are defined as follows:

$$Y'_R = -F_N \cos\delta \ / \ (\frac{\rho}{2} L \ d \ U^2)$$

$$N'_R = Y'_R \ (x_R - x_G) \ / \ L$$

where F_N : rudder normal force.

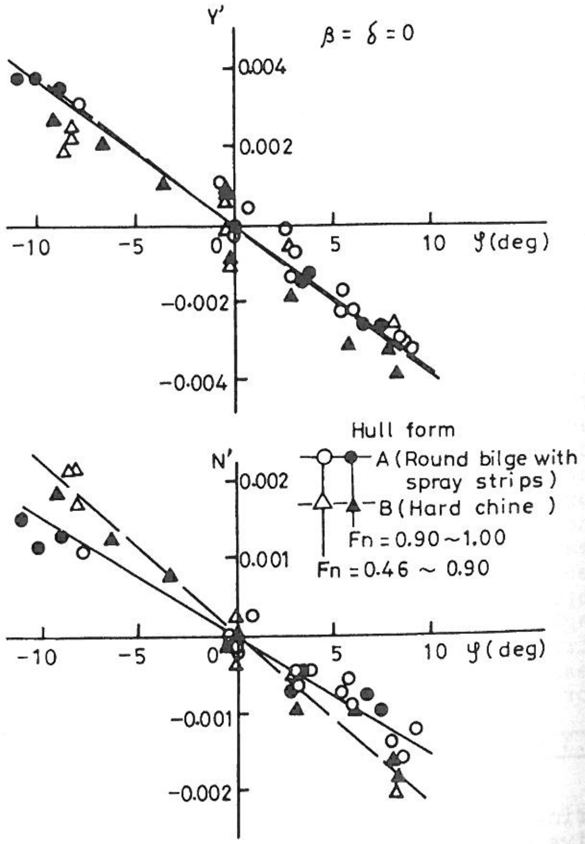

Fig. 5 Sway force and yaw moment obtained from heel angle test

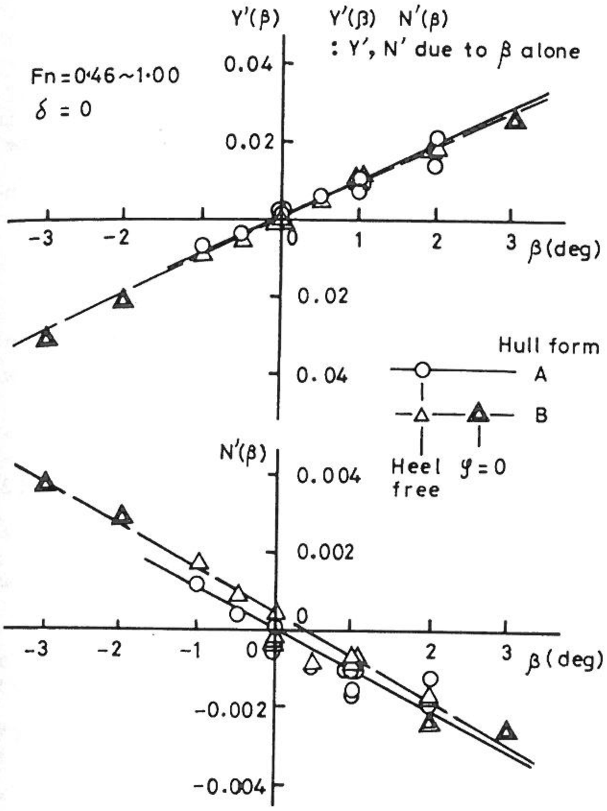

Fig. 6 Sway force and yaw moment obtained from oblique towing test

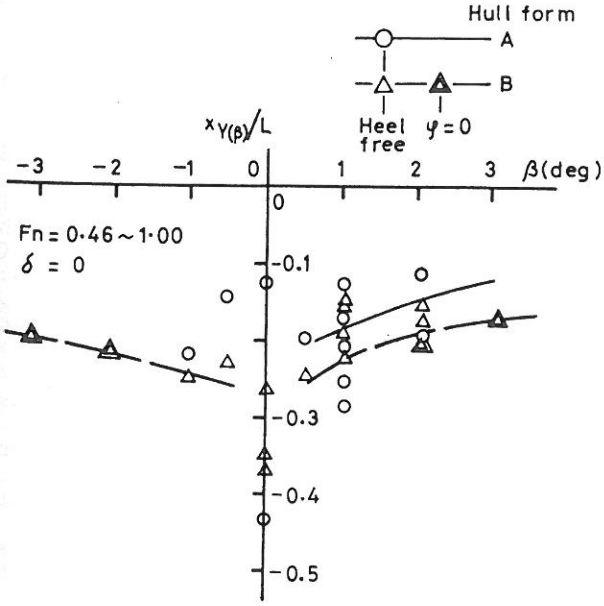

Fig. 7 Longitudinal position of acting point of sway force obtained from oblique towing test

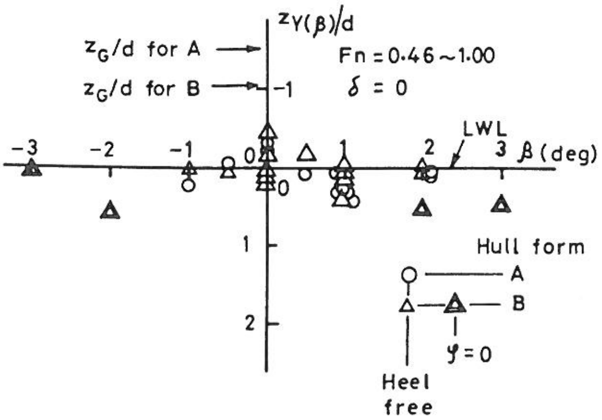

Fig. 8 Vertical position of acting point of sway force obtained from oblique towing test

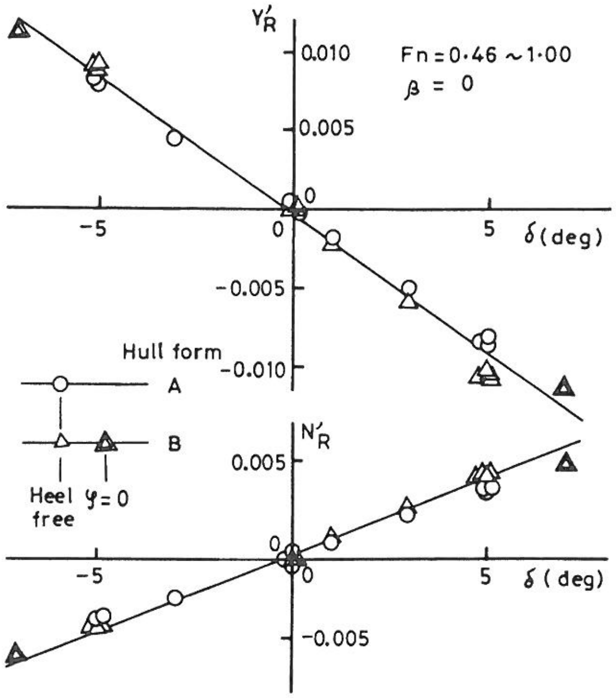

Fig. 9 Sway force and yaw moment obtained from rudder angle test

Obtained characteristics of both hull forms A and B are found very similar to one another. The results are also shown of the hull form B at which heel angle was restrained to zero. These results agree with the characteristics obtained for the heel free condition. This fact also indicates the possibility of linear superposition of δ- and φ-component forces and moments, when the tested hull form runs in the vicinity of straight course with small heel angle.

[4] Heel Angle Test for the Effect of Spray Strips

Heel angle ϕ of the model in straight course running was varied by transverse shift of a small ballast weight.

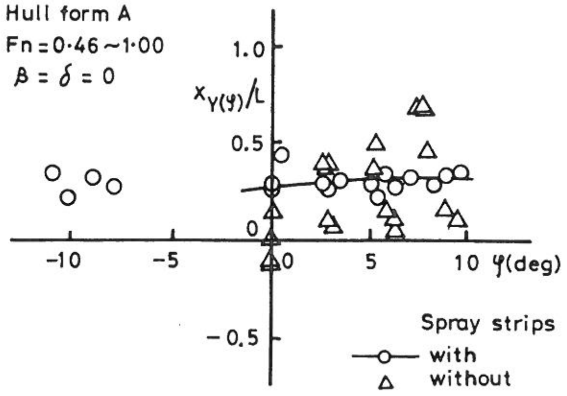

Fig. 10 Longitudinal position of acting point of sway force obtained from heel angle test

Results of the test are shown in Fig. 10, where x co-ordinates of acting point of $Y(\phi)$ are plotted versus ϕ. Considerable scattering of the results is noted for "without spray strips" condition. In other words, it can be said that the spray strips show such an effect as concentrating longitudinal acting point $x_{Y(\phi)}$ of $Y(\phi)$ to about 0.3 L. Results of z co-ordinates of acting point of $Y(\phi)$ are shown in Fig. 11. It is found that the spray strips also show an effect to raise acting point of $Y(\phi)$ by as much as about 0.5 d. As mentioned later, this effect results in less reduction of virtual GM and in added stability of sway-roll-yaw coupled motions.

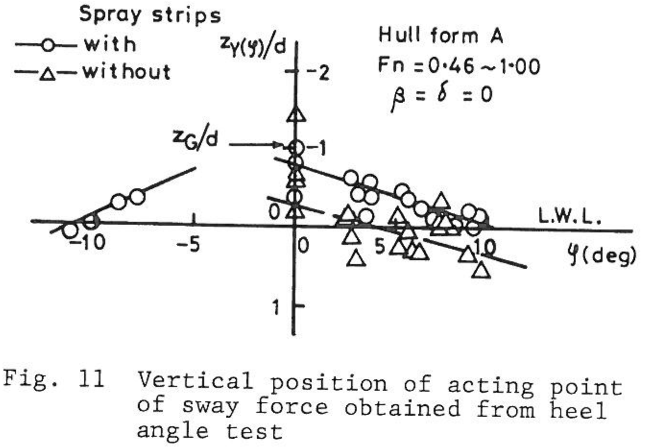

Fig. 11 Vertical position of acting point of sway force obtained from heel angle test

3. MATHEMATICAL MODEL FOR SWAY-ROLL-YAW COUPLED MOTIONS

In the present simulation study, a hull form is assumed to have single propeller and single rudder, both of which are in center line of the main hull, for the sake of simplicity. In reference to the co-ordinate systems shown in Fig. 3, the mathematical model expressed by the following equations is adopted for manoeuvring motions including roll:

$$\left.\begin{aligned} &(m + m_x)\, \dot{u} - (m + m_y)\, v r \\ &= X_H + (1 - t)\, T - F_N \sin\delta \\ &(m + m_y)\, \dot{v} + (m + m_x)\, u r \\ &= Y_H - F_N \cos\delta \\ &(I_{zz} + J_{zz})\, \dot{r} \\ &= N_H - F_N \cos\delta\, (x_R - x_G) \\ &(I_{xx} + J_{xx})\, \ddot{\phi} \\ &= K_H - F_N \cos\delta\, (z_R - z_G) \end{aligned}\right\} \quad (2)$$

$$\text{where } X_H = -(R_f + R_r) + \frac{\rho}{2} L\, d\, U^2 \cdot X'_{vr} v' r'$$

$$Y_H = \frac{\rho}{2} L\, d\, U^2 (Y'_v v' + Y'_r r' + Y'_\phi \phi)$$

$$N_H = \frac{\rho}{2} L^2 d\, U^2 (N'_v v' + N'_r r' + N'_\phi \phi)$$

$$K_H = K_{\dot{\phi}} \dot{\phi} - \Delta a\, GM\, \phi - (Y_H - m_x u r)(z_Y - z_G)$$

X_H, Y_H, N_H, K_H: hydrodynamic forces and moments acting on the hull

X'_{vr}, Y'_v, Y'_r, Y'_ϕ, N'_v, N'_r, N'_ϕ, $K_{\dot{\phi}}$: hydrodynamic coefficients
other detailed notations are referred to the list of nomenclature.

In regard to the left hand side of Eq. (2), several additional terms have been proposed hitherto (Refs.1 to 3 and 8). In the present study, however, simplest mathematical model as Eq.(2) is assumed. Making reference to the experimental results summarized in the previous sections, the right hand side of Eq.(2) has been derived from the following assumptions:
[1] Non-dimensional hydrodynamic coefficients remain constant during the motions.
[2] Sway forces $Y(\phi)$, $Y(\beta)$, and $Y(r)$ act at the mid point of draft, and this position does not move during the motions. And rudder normal force F_N acts at the mid point of rudder height.

Most of hydrodynamic characteristics appearing in Eq.(2) were obtained from the experiments as follows:

* Towing test ------------> R_r
* Propeller open test ----> T
* Self-propulsion test ---> $w(F_n)$, $t(F_n)$
* Heel angle test --------> Y'_ϕ, N'_ϕ
* Oblique towing test ----> Y'_v, N'_v, $\delta_o(\beta_R)$, $z_{Y(\beta)}/d$

where δ_o : stern flow direction at steady turning

β_R: drifting angle at rudder stock

$$\beta_R = -\tan^{-1}(v_R / u)$$

$$v_R = v + (x_R - x_G) r$$

* Rudder angle test ------- $u_{Re}/(P \cdot n_P)$

where u_{Re}: Effective inflow velocity toward rudder

* Inclining test ---------> GM
* Free rolling test ------> $I_{xx} + J_{xx}$; at $F_n = 0$

* Free rolling test ------> $K_{\dot\phi}$; at running condition

where $K_{\dot\phi}$: roll damping.

Other hydrodynamic coefficients were evaluated by the following sources or formulae:

* m_x, m_y, J_{zz}: from Motora chart (Ref.9)
* $C_N(\delta e) = 6.13\lambda/(\lambda + 2.25)\ \delta e$ (Ref.10)

where $C_N = F_N / (\frac{\rho}{2} A_R u_{Re}^2)$

δe : Effective rudder angle

$\delta e = \delta - \delta_o$

* $X'_{vr} = - \frac{1}{3}(m' + m'_y)$

* $Y'_r = -\ell'_p Y'_v \quad N'_r = -\ell'_p N'_v$ (Ref.3)

where $\ell'_p = \ell_p/L$

ℓ_p : distance from G to pivoting point.

4. SIMULATION OF SWAY-ROLL-YAW COUPLED MOTIONS

Making use of the mathematical model together with the captive model test results, calculations of sway-roll-yaw coupled motions were carried out. As for operation condition, approach speed U_s is prescribed as relatively high speed, i.e. $U_s = 40$ knots ($F_n = 0.916$) in full scale. And for designed load condition, KG and GM in full scale are adjusted as follows:

KG = 3.70 meters, GM = 1.05 meters for the hull form A,

KG = 3.70 meters, GM = 3.39 meters for the hull form B.

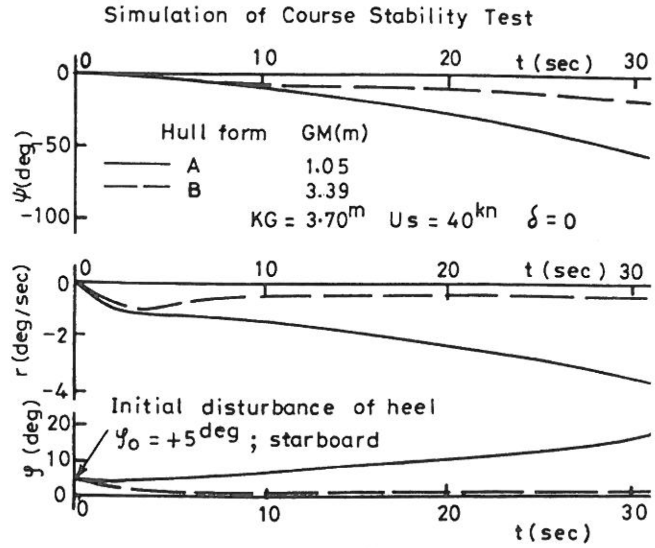

Fig. 12 Calculated manoeuvring motions of the hull forms A and B with roll coupling effect

4.1 Effect of Hull Forms

As a test mode, course stability test is adopted in which rudder angle is kept at zero and initial disturbance of heel ϕ_o = 5.0 degrees to starboard is given. Results of calculations are shown in Fig. 12. Yaw rate r and roll ϕ of the hull form A keep increasing non-oscillatorily until eventual capsizing, while r and ϕ of the hull form B non-oscillatorily tend to each steady value. Causes of these roll and yaw instabilities may be attributed to the following two effects:

[1] Effect of the hull form

Inherent course instability due to less hydrodynamical damping might have caused the apparent roll instability.

[2] Effect of GM

Relatively small GM might have caused the roll instability, and increasing roll might have induced continuous increase of yaw rate.

Considering these causes, calculations were made to obtain inherent sway and yaw, and roll motions. These inherent motions are obtained by assuming coefficients Y_ϕ and N_ϕ to be zero. Results of calculated trajectories are shown in Fig. 13. Non-dimensional rates of turn r' are plotted versus rudder angle δ in Fig. 14, where r' is defined by $r' = r\,L/U$. From these results, it can be said that the inherent hydrodynamic characteristics show no substantial difference between the hull forms A and B, and that the apparent roll induced instability is more closely related to relatively small GM rather than the difference in hull forms.

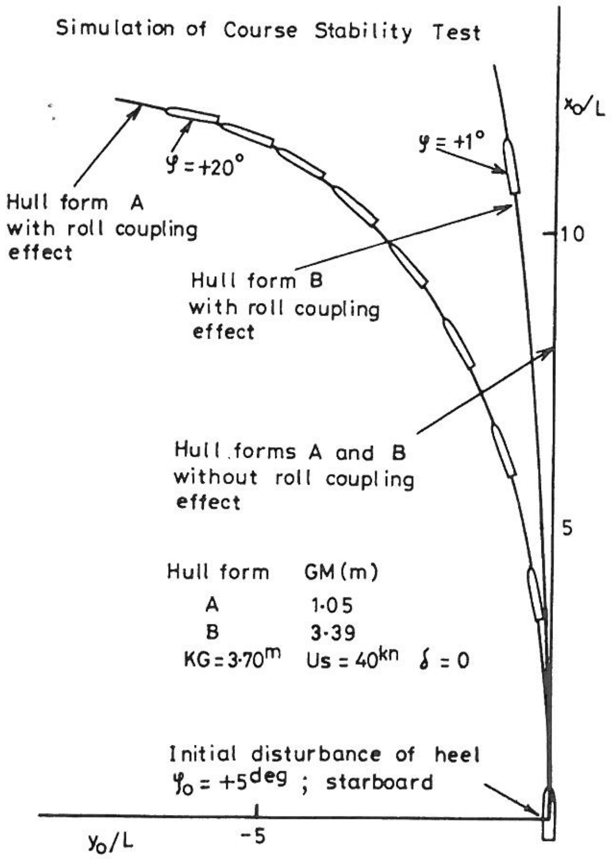

Fig. 13 Calculated trajectories of the hull forms A and B

4.2 Effect of Vertical Position of Center of Gravity

Among hull forms of high speed craft, a hard chine type one is supposed to have relatively large stiffness against the roll induced instability, in general. According to the results of simulation study in the previous section, however, the effect of difference in GM is more marked than that in the hull forms in this phenomenon. To clarify the effect of vertical position of center of gravity, calculations were made for the hard chine type hull form B. The results are shown in Figs. 15 and 16. Comparing Figs. 12 and 15, and Figs. 13 and 16, respectively, it is found that the hull form B also shows the roll induced instability when GM is decreased to the value of about 2 meters. Therefore, GM is to be carefully selected in high speed craft design even for hard chine hull forms.

4.3 Effect of Spray Strips

From the results of captive model test explained in the section 2.3 [4], in case of the hull form A, z_Y/d = 0.5 and 1.0 are

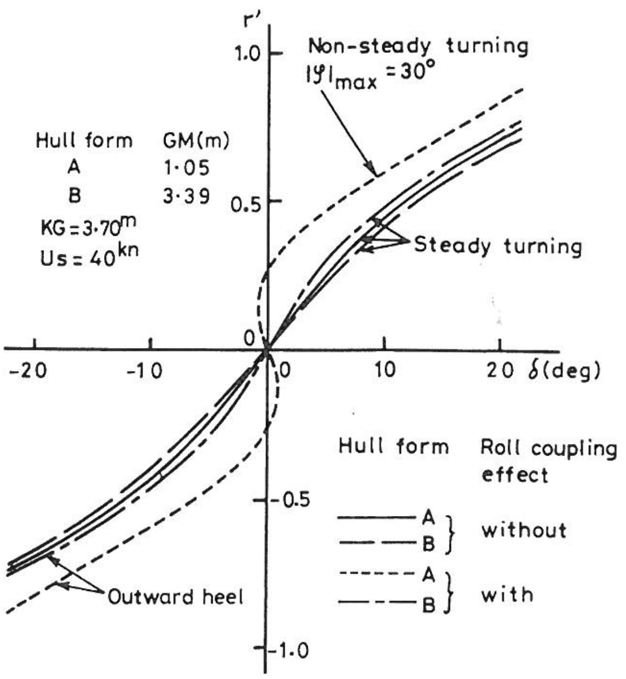

Fig. 14 Calculated non-dimensional rate of turn r' in turning test

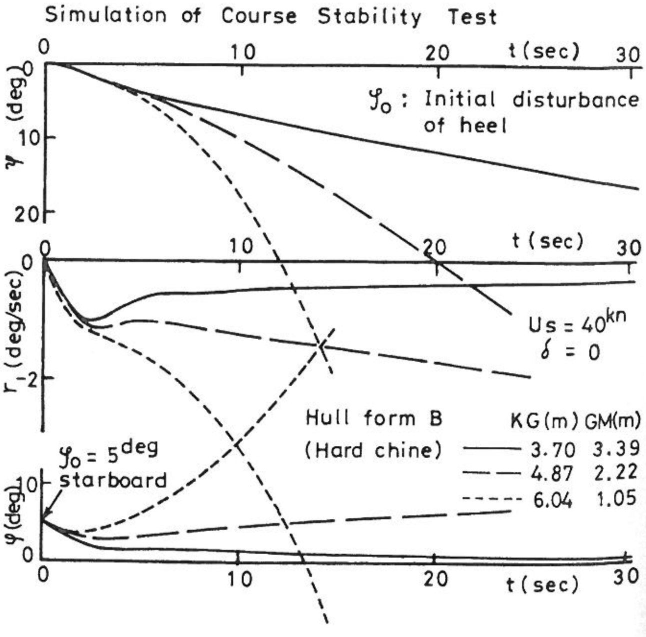

Fig. 15 Calculated manoeuvring motions of the hard chine type hull form B (Effect of vertical position of center of gravity)

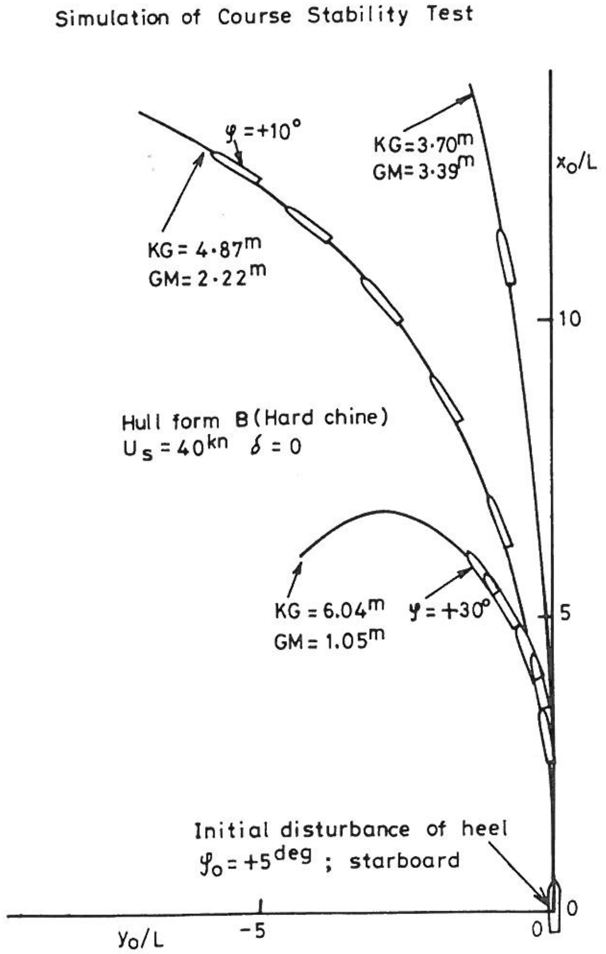

Fig. 16 Calculated trajectories of the hard chine type hull form B (Effect of vertical position of center of gravity)

considered to correspond to the hydrodynamic characteristics of "with and without spray strips", respectively. Therefore, effect of the spray strips on the roll induced instability can be calculated by varying the vertical position z_Y of acting point of sway force. Results of calculation are shown in Figs. 17 and 18, where z_Y/d shows considerable effect on manoeuvring motions. From these results, it is assured that apparent course stability is improved by the spray strips which show an effect to raise the vertical position of acting point of sway force. These calculated characteristics agree with the observed results of Suhrbier (Ref.6).

5. CONCLUSIONS

So called "roll induced instability" of high speed craft was investigated, based on the captive model test and on the simulation by use of thus obtained hydrodynamic coefficients.

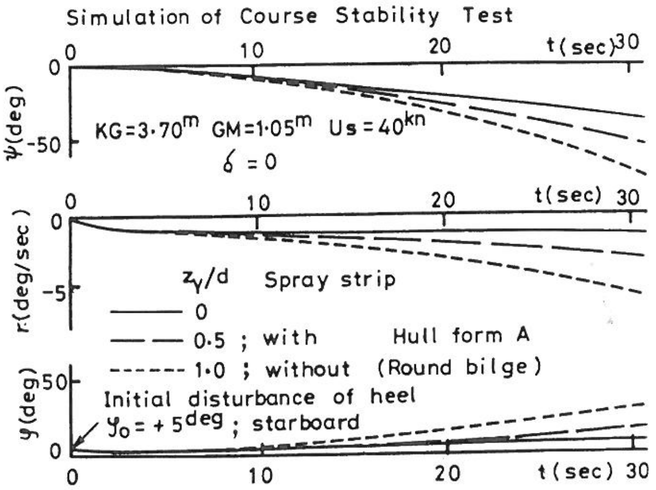

Fig. 17 Calculated manoeuvring motions of the round bilge type hull form A (Effect of spray strips)

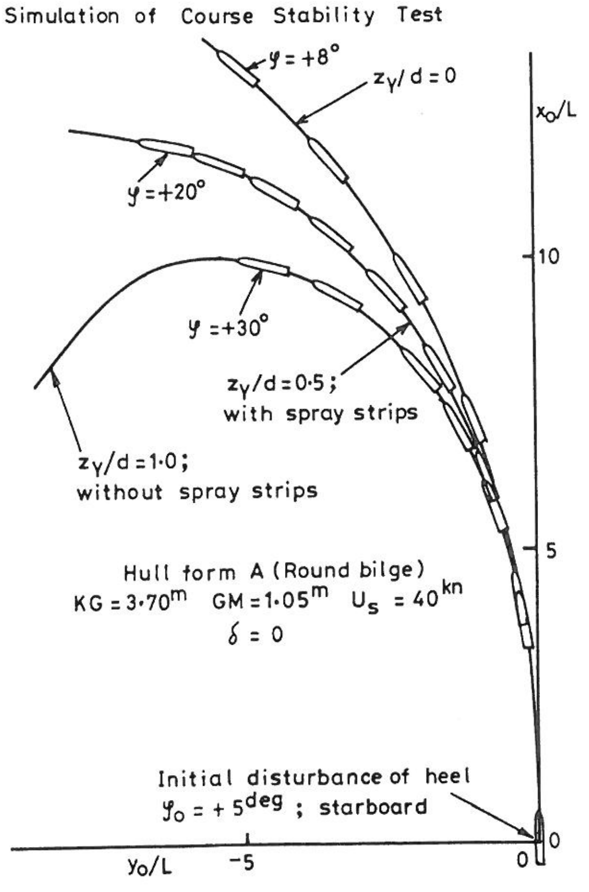

Fig. 18 Calculated trajectories of the round bilge type hull form A (Effect of spray strips)

The results of the study can be summarized as follows:

(1) Tested two hull forms, i.e. a round bilge type and a hard chine type, show only slight difference in the characteristics of sway force and yaw moment due to heel angle, drifting angle, and rudder angle.

(2) Variation in GM of the order of 0.5 meters, has a dominant effect on the phenomenon of the roll induced instability in comparison with the effect of the above mentioned difference in hull forms.

(3) Apparent course stability is improved by the spray strips which show an effect to raise the vertical position of acting point of sway force induced by heel angle.

Since the roll induced instability is directly related to the safety of operation of high speed craft, such simulation study as the present one may be considered to be helpful for stability estimation in the initial design stage. Further study will be necessary on the simulation of sway-roll-yaw coupled motions by use of more accurate mathematical model. In such a model, it will be necessary to include non-linear terms due to $\beta \cdot \phi$ and $r \cdot \phi$, together with variation of the vertical position z_Y of acting point of sway force due to large roll angle.

ACKNOWLEDGEMENT

The authors wish to express their deep appreciation to Dr. Kyoji Watanabe, Former General Manager of Nagasaki Technical Institute of Mitsubishi Heavy Industries, Ltd. for his instructive discussion. The authors also wish to express their appreciation to the members of Nagasaki Experimental Tank, for their cooperation in carrying out this investigation.

REFERENCES

1. Hirano, M. and Takashina J.: A Calculation of Ship Turning Motion Taking Coupling Effect Due to Heel into Consideration, Trans. of the West-Japan Society of Naval Architects No.59, March 1980.
2. Eda, H.: Rolling and Steering Performance of High Speed Ships, 13th Symp. on Naval Hydrodynamics, Oct. 1980.
3. Son, K. and Nomoto K.: On the Coupled Motion of Steering and Rolling of a High Speed Container Ship, J. of the Society of Naval Architects of Japan, Vol. 150, Dec. 1981.
4. Rödström, R., Edstrand, H. and Bratt, H.: The Transverse Stability and Resistance of Single-Step Boats When Planning, Publication of the Swedish State Shipbuilding Experimental Tank, Nr 25, 1953.
5. Marwood, W.J. and Bailey, D.: Transverse Stability of Round-Bottomed High Speed Craft Underway, NPL, Ship Division, Ship Report 98, 1968.
6. Suhrbier, K.R.: An Experimental Investigation on the Roll Stability of a Semi-Displacement Craft at Forward Speed, RINA Symp. on Small Fast Warships and Security Vessels, March 1978.
7. Millward, A.: Preliminary Measurements of Pressure Distribution to Determine the Transverse Stability of a Fast Round Bilge Hull, ISP, Vol.26, May 1979.
8. Ogawa, A.: On the Capsizing of a Ship in Strong Tidal Current Area, J. of Japan Institute of Navigation, Vol.57, Aug. 1977.
9. Motora, S.: On the Measurement of Added Mass and Added Moment of Inertia for Ship Motions (Part 1 to 3), J. of the Society of Naval Architects of Japan, Vol. 105 and 106, July 1959 and Jan. 1960.
10. Fujii, H.: Experimental Researches on Rudder Performance (2), J. of the Society of Naval Architects of Japan, Vol. 110, Dec. 1961.

Discussion

M. Hirano (Akishima Laboratory, Mitsui Engineering and Shipbuilding Co., Ltd., Japan)

I congratulate the authors on this fine paper and would like to comment on the following points.

(1) In general, due to changes in trim and sinkage and due to wave-making phenomenon, maneuvering hydrodynamic forces of high-speed ships are affected not a little by their advance speed. In Figs. 5 and 6, the experimental results of the maneuvering hydrodynamic forces are summarized with one straight line for each hull form, which implies that there would be no speed effects on the maneuvering hydrodynamic forces. Regarding this point, I feel that more data with respect to the effects of the advance speed would be needed in order to reach to such a conclusion as the above.

(2) Regarding yaw moment $N'(\beta)$, Fig.6 shows negative sign of $N'(\beta)$ for positive sign of β, while conventional displacement type ships generally have characteristics of positive $N'(\beta)$ for positive β. Are the facts shown in Figs. 6 and 7 special features of which such semi-displacement type high-speed ships as those employed in this study are usually possessed?

Author's Reply

The authors wish to appreciate the discussions of Dr. Hirano. With regard to the first comment; observed difference of trim was less than 1.0% of ship length within the range of Froude number we tested, i.e. from 0.46 to 1.00. And we could not find speed effects on the non-dimensional manoeuvring derivatives.

However, as shown in the paper by Mr. Mueller-Graf and Prof. Schmiechen, some variations in hydrodynamic coefficients might have speed effects beyond Froude number 1.0.

With regard to the second comment; at the beginning of our captive model tests, we also felt it strange that variations in yaw moment N' versus drifting angle β were different from those of conventional displacement type ships, as Dr. Hirano suspected.

After careful examination of our experimental results, however, we confirmed that these characteristics are one of typical features of semi-displacement type high speed boats.

M. Schmiechen (VWS Berlin Model Basin, FRG)

The work done by our colleagues of MHI at Nagasaki is greatly appreciated. One point disturbing us is the fact, that two vehicles of so widely differing values of the metacentric height have been compared. In my opinion this difference is bound to blur all the other effects. A second point is that the values of most of the hydrodynamic quantities have been estimated only widely. I wonder whether the authors have carried out sensitivity tests. According to my experience this type of study is notoriously difficult if stability is marginal.

Author's Reply

We appreciate the discussions of Prof. M. Schmiechen. Regarding the first comment; we carried out this investigation under the specified condition. That is, from the practical viewpoint, the same KG was adopted for both hull forms of round bilge and hard chine crafts. Furthermore, we carried out simulations for the hard chine craft with the same GM as that of the round bilge one. As the results of the simulations, similar roll induced instabilities were obtained for both round bilge and hard chine crafts. And these qualitative characteristics have been confirmed by the free-running model tests.

Regarding the second comment; firstly we carried out simulations to clarify the effects of roll damping and transverse radius of gyration. And we found that they have negligibly small effects on the steady turning characteristics. We then carried out simulations for two different hull forms, for hard chine craft with various GM, and for round bilge with and without spray strips. These simulation studies are considered to be a sort of sensitivity tests. Moreover, the free-running model tests confirmed the validity of the present mathematical model.

W.G. Price (Brunel University, UK)

My congratulations and gratitude are extended to the authors for their extremely competent experimentation and presentation of their data.

The authors in their mathematical modelling employ correctly coupled sway-yaw-roll equations and not separate the equations into coupled sway-yaw together with a single degree of freedom roll equation. From my experience it is in general impossible to derive their experimental findings using the latter simplified mathematical model and a totally coupled set of equations is essential. However, if the authors had adopted non-dimensional equations of the 'parmi' type using a suitable or modified length parameter then it is clearly seen that the coefficient most affected by speed is the term GM/U^2 in the non-dimensional roll restoring expression. As U increases for fixed GM or GM decreases for fixed U the term GM/U^2 decreases and from a linear stability analysis it can be shown that the ship model becomes unstable. In fact a region of stability based on GM and U can be derived and a simple stability criteria may be produced to demonstrate this. Naturally a more complicate mathematical model may be produced by including other possible dynamical influences (e.g. change in trim, displacement etc.) in the variation of the hydrodynamic derivatives and this enables further refinement and differentiation of the behaviour of the two ship models.

Author's Reply

Regarding to the comment by Prof. Price, we completely agree to his point. Correctly speaking, GM itself does not have dominant effect, but GM/U^2 has. That is, the same hull with the same GM shows no instability at a low advance speed, and experiences instability at a higher speed. This is due to the fact that roll restoring moment provided by the initial GM is canceled by the hydrodynamic unstable moment which is proportional to the square of advance speed.

Incidentally we could not include the results of free running model test and simulation calculation showing the effect of advance speed on the roll-induced instability. In this context, we are very grateful to Prof. Price for giving us a chance to add an explanation to this point.

B. Mueller-Graf (VWS Berlin Model Basin, FRG)

I like to congratulate the authors on their very interesting paper concerning the stability of high speed craft underway. By means of simulation studies the authors underline the dominant effect of the metacentric height on the roll induced instability of semi-displacement craft also at high speeds. The computations confirm the present practice in designing high speed craft to overcome stability problems by selecting a high value of GM. On the basis of heeling tests the authors report that the tested hull forms despite the great differences in section shape, buttock curvature and length-beam ratio cause only slight differences in the characteristics of sway force and yawing moment. This seems to be very surprising and not in accordance with references [5,6].

In this paper, which is related to high speed craft, no figure shows results or derivatives represented versus speed. It must be assumed, that the authors are neglecting the speed only because they found out - on the basis of heel angle tests - that speed has no substantial influence on the sway force and yaw moment. This statement does not agree with the results of references [5,6] and with those obtained at VWS Berlin Model Basin in an investigation of the stability of semi-displacement crafts. We experienced, as reported in the paper before, a remarkable effect of speed on stability mainly at $F_n>0.8$.

The conclusion that the apparent course stability is improved by spray rails which raise the vertical position of the centre of sway force should be underlined. But it must be pointed out that the amount of raise depends on the height of the rails above the waterline. At VWS spray rails which intersect the waterline or which are arranged close to it are preferred. In this case the height of the acting point of sway force is less than the half of the reported value.

In Fig.11 the vertical position of the acting point of sway force lies predominantly above DWL. In the simulation study the sway forces are assumed to act at the midpoint of draft. Can the authors explain the reason for departing from the test results?

Author's Reply

We appreciate the discussions and comments by Mr. Burkhard Mueller-Graf. For the first and second comments of his discussions, we are afraid he might have some misunderstanding. In references [5 and 6], the increase of heel angle is only measured They never dealt with hydrodynamic forces and moments through experiments, and did no report any results which can be compared with ours. We only concluded that non-dimensionalized sway forces and yaw moments have similar characteristics for the tested two hull forms. We suppose it is partly due to appropriate non-dimensional form as shown by Eq.(1). We mentioned that there is no substantial dependency in non-dimensional sway forces and yaw moments, not swa forces and yaw moments themselves, on the basis of not only heel angle test but also oblique towing and rudder angle tests. We have already admit in the reply to Dr. Hirano's discussion that we expect Froude number dependency for Y' and N', and that the reason why we get no substantial Froude number dependency up to Fn=1.0 would be the fact that the variation of trim angle is relatively small.

Concerning the effect of spray strips, we appreciate your results for another arrangement of spray strips.

With respect to the fourth comment; as shown in Fig.11, vertical position of acting point due to roll is lowered with the increase of heel angle. The more that vertical position is lowered, the severer the roll induced instability becomes. If we assumed that hydrodynamic sway forces act above DWL by adopting the data within the range of small roll angle, we might underestimate the effects of sway force on the roll-induced instability. To obtain a stable result of simulation for a design which is unstable in reality is most dangerours and should be avoided.