AN INVESTIGATION INTO THE COMBINED EFFECTS OF TRANSVERSE AND DIRECTIONAL STABILITIES ON VESSEL SAFETY

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The paper reviews briefly previous attempts to account for the influences of directional stability on transverse stability before putting forward a procedure whereby the two can be treated in parallel and their combined effects on safety investigated. Application of the proposed procedure to a wide beam riverboat is considered and the results are presented and discussed. The investigation undertaken clearly indicates that under certain circumstances directional instability can lead to large heeling angles and possible loss of control, causing a serious threat to vessel safety.

INTRODUCTION

In ship stability studies it is common to investigate the occurrence of loss of stability, which may eventually lead to capsizing, as a single cause-effect relationship. In many cases, however, such an approach is not supported by practical experience, since capsizing can frequently be the final result of combined actions, appearing in a chain of events which gradually reduce the safety margin of the vessel. The HERALD OF FREE ENTERPRISE disaster can be cited as a typical situation where factors such as high speed in shallow water, trim by the bow, loss of control, human error and inadequate subdivision, played a critical role in leading to the capsize.

To be able to define scenarios and then satisfactorily model all the phenomena contributing to loss of transverse stability, together with their interactions, would be the ideal case, but this represents an admittedly immense task at present. For certain situations, however, like the combined effect of transverse and directional stability, a qualitative understanding of the mechanism generating a high risk situation can be obtained with the current state of knowledge.

This paper, focusing on the last point, represents an initial stage of wider scale research on ship stability, ship controllability and their interrelationship under various environmental conditions. On the basis of such a perspective, single GM-based stability criteria could be subject to re-evaluation. If, for example, "adequate" GM implied also a largely directionally unstable vessel, then the risk of losing control and hence being subjected to unfavourable external excitations possibly leading to significant reductions in GM would be higher. At this level of complexity, to attempt to quantify the overall threat would, of course, be very difficult, but thinking in terms of risk, it could very well be possible that what in the first instance looks safer, could in real life be exactly the opposite.

The investigation presented herein is

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based on a detailed surge-sway-yaw-roll non-linear mathematical model where, by making use of appropriate numerical techniques, time simulation, steady states continuation and analysis of stability properties of each steady state are performed. With these tools the effects of trim by bow, GM and forward speed on both the directional and transverse stability are examined and thereafter the occurrence of dangerous situations as represented by large heeling angles, is identified.

In particular, the study puts emphasis on the non-linear character of the behaviour of the system and its possible consequences for safety.

BACKGROUND

Problems of coupling between planar motions and rolling in ships operating at high speed are well known and have in many cases been the subject of investigation, either from a stability or from a manoeuvrability point of view, e.g. [1], [2], [3], [4]. For this reason, various mathematical models have been developed, usually in three (sway, yaw, roll) or in four (surge, sway, yaw, roll) degrees of freedom. A number of these are linear, e.g. [5], [6], and others non-linear, [2], [7]. The narrower topic of the relationship between transverse and directional stability, however, has not received sufficient attention, with the exception perhaps of the literature dedicated to the broaching-to phenomenon, e.g. [8], [9].

In a recent investigation, [6], regions of instability were identified for the coupled sway-yaw-roll motions of a ship trimmed by the bow (in which condition directional stability is generally poor). In this paper, it was suggested that bow-trim-induced instability can cause large "divergent" or "oscillatory" motions, possibly leading to capsize, even though the metacentric height is positive. It was, however, not possible to gain further insight as the approach was limited by its very nature, trying to explain purely non-linear phenomena with linear theory tools. The local analysis performed allowed only for the identification of the existence of unstable equilibria. It could not, for example, predict the convergence of the system to a neighbouring stable state characterised by a steady rate of turn and heeling angle when an initial perturbation was applied to it at an unstable equilibrium position (see Fig. 1).

Emphasis on identifying these nearby stable states in the phase space and their basins of attraction would be far more important from a safety point of view rather than testing for instability at the upright zero rate of turn position, which is a rather common phenomenon for operating ships.

MATHEMATICAL MODEL

For the purpose of this investigation, a non-linear modular mathematical model was used, with four degrees of freedom, as given below (see also Fig 2):

$$\text{surge: } m(\dot{u} - rv - x_G r^2 + z_G p r) = X_H + X_R + X_P$$

$$\text{sway : } m(\dot{v} + ru + x_G \dot{r} - z_G \dot{p}) = Y_H + Y_R \quad (1)$$

$$\text{yaw : } I_z \dot{r} + m x_G(\dot{v} + ru) = N_H + N_R$$

$$\text{roll : } I_x \dot{p} - m z_G(\dot{v} + ru) = K_H + K_R$$

where for the hull forces and moments:

$$X_H = X_{\dot{u}} \dot{u} - Y_{\dot{v}} v r - Y_{\dot{r}} r^2 + X_{vr} v r + \mathrm{Res}(u)$$

$$\begin{aligned} Y_H = {} & Y_{\dot{v}} \dot{v} + Y_{\dot{r}} \dot{r} + Y_v v U + Y_r r U + \\ & + Y_{vv} v|v| + Y_{rv} v|r| + Y_{rr} r|r| + \\ & + Y_\varphi \varphi U + Y_{v\varphi} v|\varphi| + Y_{r\varphi} r|\varphi| \end{aligned}$$

$$\begin{aligned} N_H = {} & N_{\dot{r}} \dot{r} + N_{\dot{v}} \dot{v} + N_r r U + N_v v U + \\ & + N_{rr} r|r| + N_{rrv}(r^2 v/U) + \\ & + N_{vvr}(v^2 r/U) + N_\varphi \varphi U^2 + \\ & + N_{v\varphi} v|\varphi| U + N_{r\varphi} r|\varphi| U \end{aligned}$$

$$K_H = K_{\dot{p}}\ddot{\varphi} + C(\dot{\varphi}) + R(\varphi) - z_Y Y_H$$

The manoeuvring coefficients were calculated according to [10] and [11]. The terms accounting for the effect of heeling on the sway and yaw linear coefficients ($N_{v\varphi}$, $N_{r\varphi}$ etc) were taken from [7]. The yaw damping $C(\dot{\varphi})$ was calculated as suggested in [12] while the restoring moment was derived from the hull sections at various heeling angles with a seventh order polynomial being fitted to the results.

In addition, the propeller generated thrust was modelled by :

$$X_P = (1-t)\rho n^2 D^4 K_T$$

with

$$K_T = C_0 + C_1 J_p + C_2 J_p^2$$

For the rudder forces and moments, expressions from [7] were used, e.g.

$$N_R = -(1+a_H)x_R F_N \cos\delta$$

The rudder to hull interaction term a_H was taken from [13].

For the effect of trim on hydrodynamic coefficients, expressions are available from [10] or [14]. Trim correction factors from [10] are more moderate and they were preferred for this study.

STABILITY ANALYSIS

After a number of transformations, equations (1) can be brought in the vector form:

$$\dot{\mathbf{z}} = \mathbf{F}(\mathbf{z},\mathbf{a}) \tag{2}$$

where, $\mathbf{z}$ is the state variables vector, $\mathbf{z} = (u,v,r,p,\varphi)^T$ and $\mathbf{a}$ is a control parameter, varying independently, which can be any of the rudder angle, trim, and propeller rate.

At points of static equilibrium $\dot{\mathbf{z}}$ must be zero and (2) gives:

$$\mathbf{F}(\mathbf{z}(\mathbf{a}),\mathbf{a}) = 0 \tag{3}$$

To derive the dependence $\mathbf{z}(\mathbf{a})$, a technique borrowed from Bifurcation analysis is used, based on [15], which automatically traces the steady states curve, passing without any difficulty over limit points. The technique is based on a differentiation of equations (3) with respect to a parameter l accounting for the length of the solution curve, followed by a transformation into an initial values integration problem. For stability analysis, local linearisation around each solution point z_0 is performed by substituting $\mathbf{z} = \mathbf{z}_0 + \mathbf{b}$ into (2), where $\mathbf{b}$ is the vector of deviations from the solution $\mathbf{z}_0$, yielding, finally:

$$\dot{\mathbf{b}} = \mathbf{C}\ \mathbf{b}$$

where, $\mathbf{C}$ is the jacobian matrix of $\mathbf{F}$. To test for stability, the signs of the real parts of the eigenvalues of $\mathbf{C}$ are examined, the existence of positive real parts signifying instability, either nodal or oscillatory.

APPLICATION

To apply the above procedures, a riverboat was selected, the main particulars of which are given in Table 1. The following effects were investigated:

a) **Effects of Trim by the Bow**

Three conditions were considered:

- even keel
- 0.4m trim by the bow (0.6 degrees)
- 1.0m trim by the bow (1.53 degrees)

In each case the variation of the steady states of the system for different rudder angles was recorded, followed by the identification of regions of instability (e.g. Figs. 3). As shown in Fig. 4, the dimensions of the instability region are increasing significantly with trim, implying also larger heeling angles at the nearby stable states (in the region of zero rudder angle). Therefore, as the vessel becomes more directionally unstable with bow trim, its stable states keep aloof from the unstable upright position, causing possibly considerable heeling. An important observation was that the maximum steady heeling occurs in general at small rudder angles. The maximum transient heeling also increases with trim (Fig. 4). This arises, however, when the rudder is considerably deflected (around 30 degrees). It must be emphasised that the situation would be further aggravated if the reduction of restoring due to bow trim were taken into consideration.

b) **Effects of Metacentric Height, GM**

In deriving Fig. 4 the value of the metacentric height, GM, was kept consistently high at 2.0m. However, since GM is critical in judging stability, its effect was further examined in the following two cases:

In the first case, GM was related to the vertical loading distribution (KG) and as such it was treated as a parameter independent of the hull form. Figs. 5 to 7 show that the instability loop size, and the heeling angle reduce with increasing GM. The effect on the turning performance of the vessel, however, was characterised by a trend towards a larger tactical diameter (Fig. 8).

In the second case, GM was linked to the hull form. Subsequently, a change of its value would imply also a modification to both the manoeuvring and stability coefficients. Under these circumstances, directional instability was eventually eliminated by reducing GM. Heeling angles during turn, on the other hand, were considerably increased (Fig. 9).

c) **Effects of Speed**

The last factor whose effect was investigated was the initial forward speed. Figs. 10 and 11 indicate that, by increasing speed, the instability loop width is reducing slightly, while loop height and maximum inclinations tend to increase. It is interesting to note that in this case linear theory would predict an increase of instability with speed. If, however, loop width is taken as a measure of instability the reverse is actually true.

CONCLUDING REMARKS

A significant finding based on the work presented in the foregoing is that bow trim can generate almost complete loss of control, in the sense that the instability region grows to the extent of occupying most of the control space of the system (for example, directional instability of ± 17 degrees was noticed at 1.00m bow trim). If such a situation arises, the pilot is likely to attempt to regain control by setting the rudder to a large angle. If this occurred at high speed, low GM and unfavourable external conditions, large heeling could arise with unpredictable implications.

It is further interesting to note that bow trim would allow for the occurrence of relatively large steady heeling angles at around zero rudder setting. Therefore, even in the absence of any effective control action large inclinations could be experienced as the system would be seeking a rather distant stable equilibrium.

Although the analysis was confined at this stage to the calm sea case, the above ideas bear heavily on a waves environment. Induced trim by the bow is then possible, either periodic (large pitch motion) or steady (the ship travelling with the bow "in the wave", in low frequency following seas). In such a condition the slightest disturbance would cause the ship to veer off course and be brought to the dangerous beam waves position, while the pilot would be unable to apply any correcting action. Should this happen, capsizing could be a likely consequence depending on the vessel conditions.

NOMENCLATURE

m : ship mass
u, v : surge, sway, velocities resp.
r, p : yaw, roll, angular velocities resp.
x_G, y_G, z_G : Co-ordinates of centre of gravity
X_H, Y_H, N_H, K_H : surge, sway, yaw roll hull forces and moments, resp.
X_p : longitudinal propeller force
X_R, Y_R, N_R, K_R : surge, sway, yaw, roll rudder forces and moments, resp.
Res (u) : resistance
I_x, I_z : moments of inertia with respect to x and z axis resp.
$C(\dot{\varphi})$: hull damping moment
$R(\varphi)$: restoring moment
U : ship speed
Z_Y : Z co-ordinate of the point of action of the lateral force, Y_H
J_p : propeller advance
K_T : thrust coefficient
t : thrust deduction
ρ : water density
n : propeller rate of rotation
D : propeller diameter
x_R : rudder position
a_H : hull-to-rudder interaction factor
F_N : rudder normal force
δ rudder angle
φ heeling angle

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TABLE 1 : Vessel's Main Dimension

Type		River-Boat
Length	L (m)	= 37.45
Beam	B (m)	= 7.93
Draught	T (m)	= 1.52
Block Coeff.	C_b	= 0.632
Service Speed	V_s (kn)	= 10
Downflooding Angle	φd	= 12^{o}

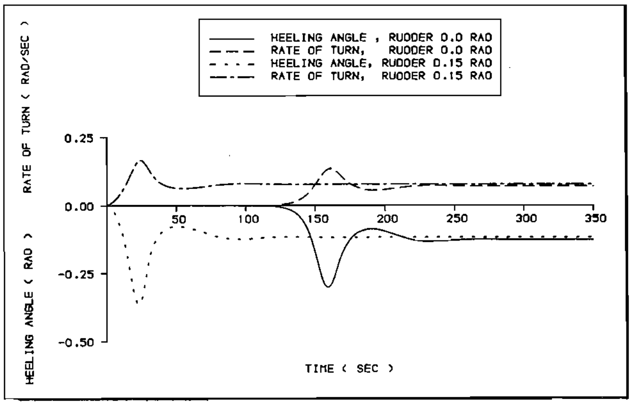


Fig. 1 : Convergence to a nearby stable state : GM = 0.5m

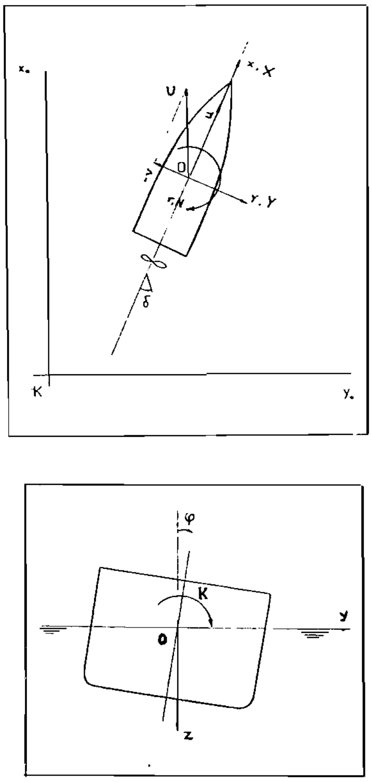
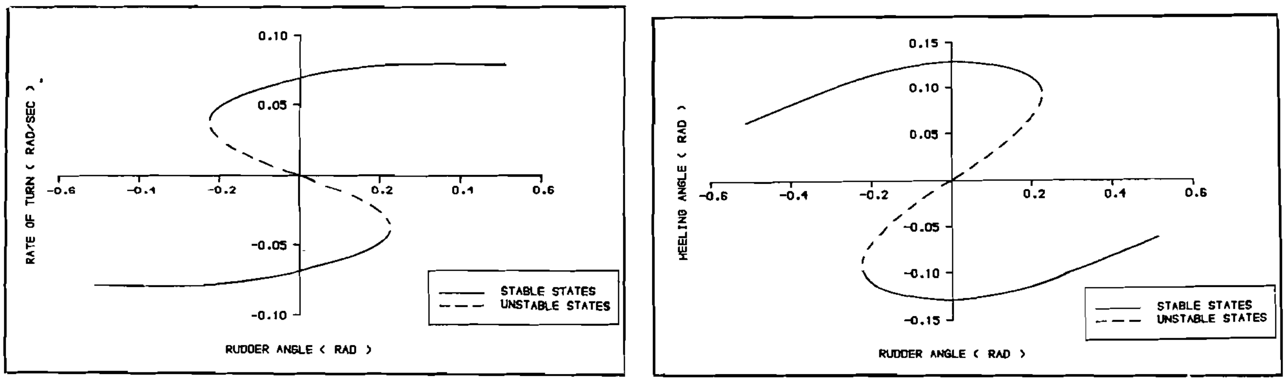


Fig. 2 : Systems of co-ordinates



(3a)

(3b)

Fig. 3 : Region of instability : GM = 0.5m

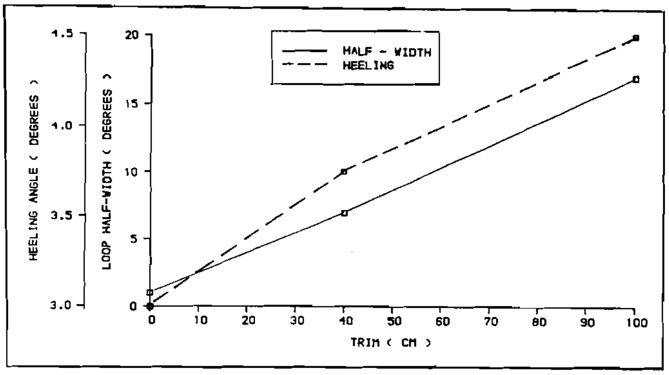
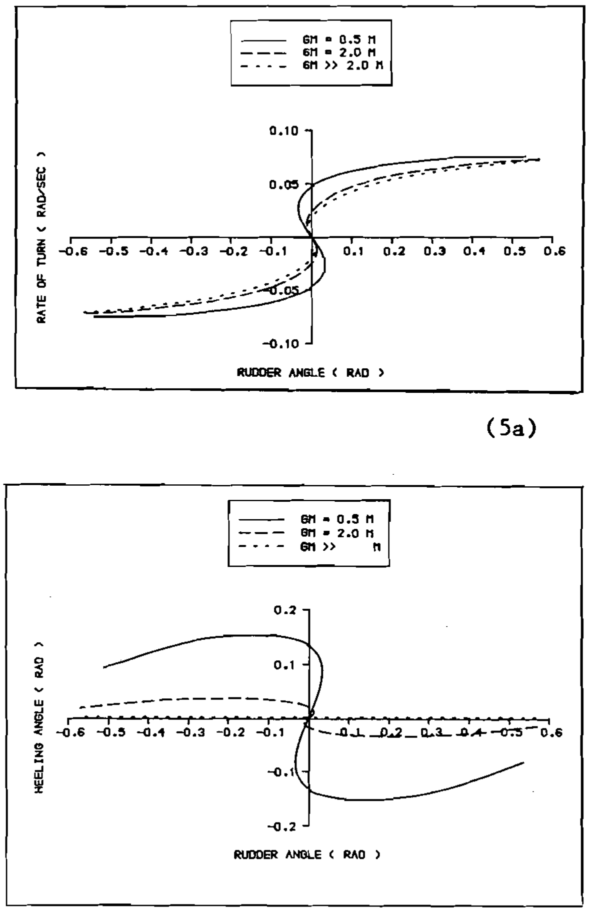


Fig. 4 : Instability loop and transient heeling versus trim : GM = 2.0m



(5a)

(5b)

Fig. 5 : Effect of GM : Trim = 0.0m

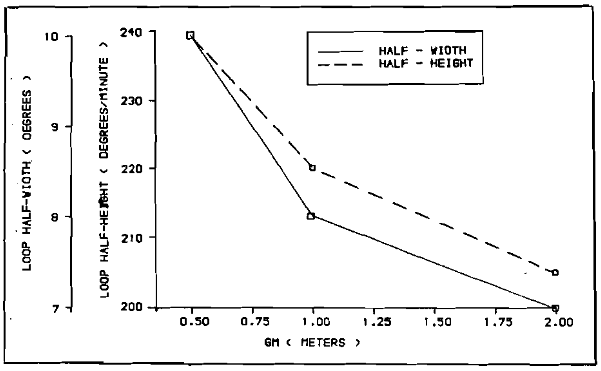


Fig. 6 : Instability loop versus GM : Trim = 0.4m

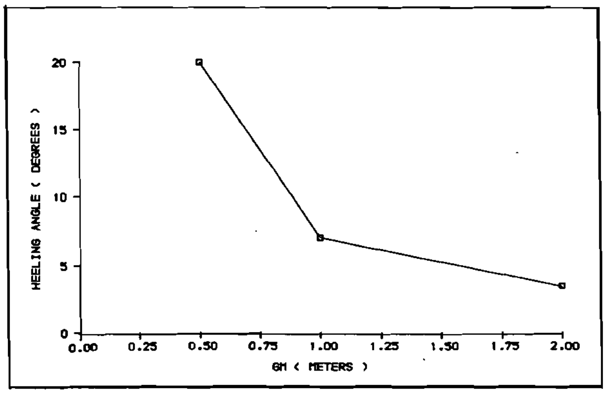
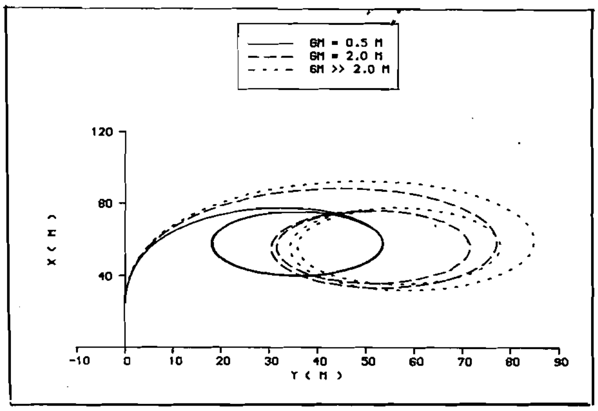
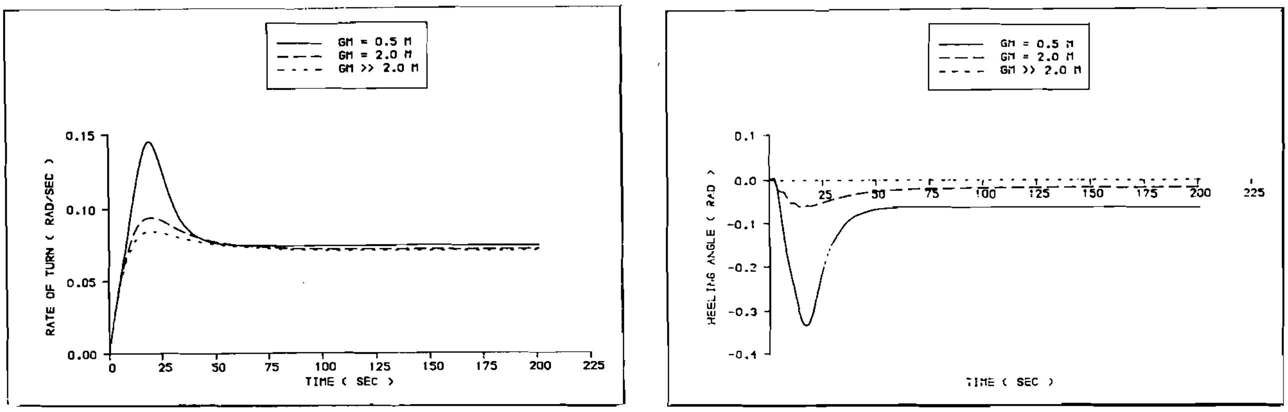


Fig. 7 : Transient heeling versus GM : Trim = 0.4m

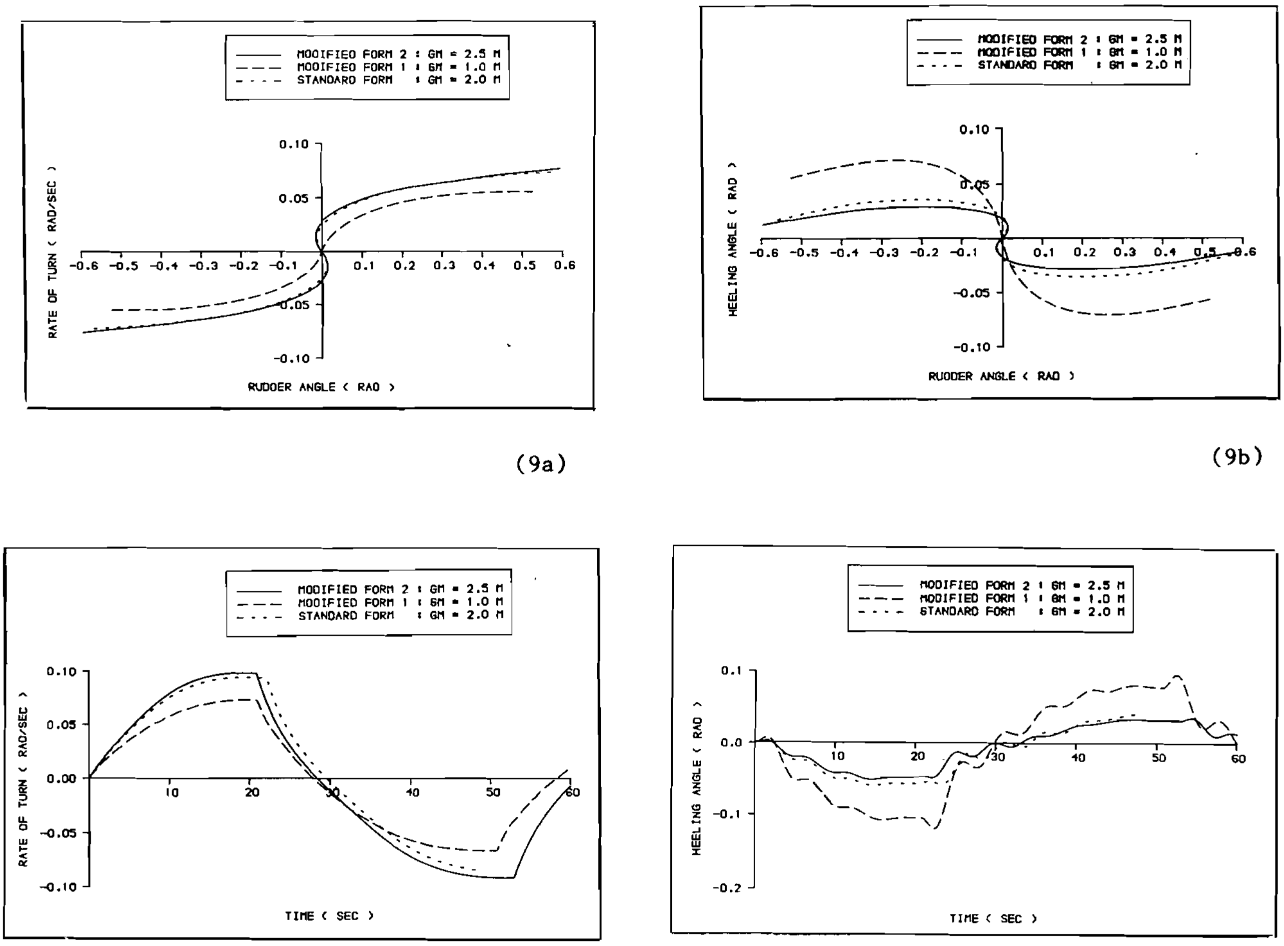


(8a)



(8b) (8c)

Fig. 8 : Turning manoeuvre



(9a) (9b)

(9c) (9d)

Fig. 9 : Effect of GM

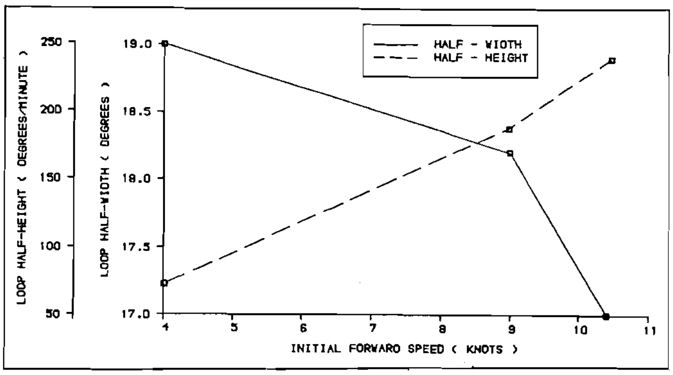


Fig. 10 : Effect of speed on instability region : Trim = 1.0m

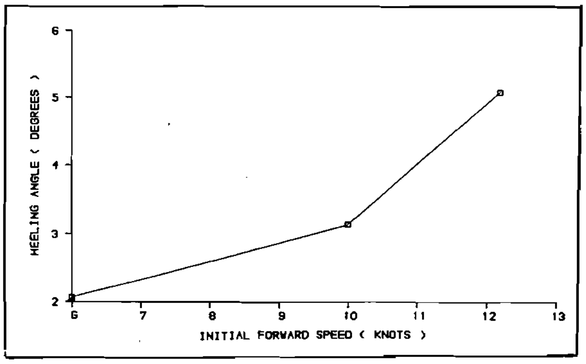


Fig. 11 : Effect of speed on transient inclination : GM = 2.0m