THE EFFECTS OF TRIM BY BOW : A DYNAMICAL SYSTEMS APPROACH

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The paper briefly reviews previous attempts to account for the adverse effect of bow trim on the safety of a vessel under way before describing a rigorous treatment based on a dynamical systems approach. A four-degrees-of-freedom non-linear mathematical model is used, accounting for coupled surge, sway, yaw and roll motions. Treating bow trim as a control parameter, its influence on directional stability is clearly demonstrated through application of the developed procedure to a wide beam riverboat in a variety of operating conditions. The paper then proceeds to present an investigation of the case of the HERALD OF FREE ENTERPRISE, where the capsize mechanism put foward as the most likely is a scenario based on the interplay between directional and transverse stabilities, initiated by bow trim and aggravated by the ingress of water on the car deck.

1. INTRODUCTION

It has been known for many years that trim by the stern enhances the directional stability of a ship whereas one trimmed by the bow is likely to have reduced controllability. Directional stability will also be affected by shallow water, although there is still some uncertainty as to whether and when this has a positive or negative effect. What is universally accepted with reference to ships under way in shallow waters is the phenomenon of "squat", which could result in sinkage and trim of a vessel, the magnitude of which increases rapidly with increasing depth Froude Number, **(1)**. To complete this resume of known facts, the coupling of yaw and roll should be mentioned. Ro-Ro vessels appear to be particularly vulnerable, where changes in course could give rise to large heeling angles.

Trim by bow would appear to be a very influential factor in all these cases. This is the factor specifically addressed by this paper, by the adoption of a fresh approach based on dynamical systems theory using a four-degrees-of-freedom non-linear manoeuvring model. The adverse effects of trim by bow are first demonstrated through application to a wide-beam river boat, and the findings are subsequently used to propose and test a capsize scenario for the HERALD OF FREE ENTERPRISE.

With reference to the facts outlined above, the following details can be found in the Report of the Court of Enquiry into the sinking of the HERALD OF FREE ENTERPRISE, **(2)**:

a) The vessel was excessively trimmed by bow while under way (approx. 0.8m).

b) The vessel capsized in shallow water (approx 12m. deep).

c) Because of the restricted water depth and the high transit speed, the vessel suffered severe sinkage and additional trim, and this, combined with the bow wave (which is also sensitive to water depth and vessel speed) allowed water to enter through the bow doors.

d) At the initial stages of the capsize the helmsman warned the captain that even with full port helm he could not control the vessel's turn.

e) The vessel heeled to starboard, then suddenly to port and thence she heeled progressively until capsizing within four minutes.

To sum up therefore, the vessel was trimmed by the bow and because of that her controllability was reduced; additionally, because she was moving at high speed in shallow waters, water started entering through the bow doors. It would be natural, therefore, to assume that the capsize of the HERALD OF FREE ENTERPRISE was the result of combined actions appearing in a chain of events which gradually reduced the safety margin of the vessel. The single-cause-effect relationship which is normally adopted in ship stability studies will, therefore, not be appropriate here. On the other hand, defining scenarios which involve the loss of transverse stability would require modelling of all the contributory phenomena together with their iterations, which would be an immense task.

Taking the road of multi-cause-effect relationships, this paper addresses the interplay between directional and transverse stabilities by placing emphasis on the non-linear character of the vessel's behaviour.

2. BRIEF REVIEW

Problems of coupling between the planar motions and the rolling of ships have been the subject of investigation on several occasions, from the point of view of either stability or manoeuvrability, see, e.g., **(3)**, **(4)**, **(5)**, **(6)** **(7)**. A problem of this nature is also addressed in research with regard to the broaching-to phenomenon, see **(8)**.

In a recent investigation, **(7)**, possible adverse effects of trim by bow were shown, by identifying ranges of instability on the basis of a linear sway-yaw-roll mathematical model. In that 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. However, the possibility of gaining deeper insight was hampered by the very nature of the adopted approach, where attempting to explain purely non-linear phenomena by using linear theory was not possible. The local analysis performed allowed only for the identification of the existence of unstable equilibria. The possibility could not be foreseen, however, that the system would converge to a neighbouring stable state characterised by a steady rate of turn and heeling angle once an infinitesimal disturbance was applied to it in a position of unstable equilibrium (see Fig. 1). Emphasis on identifying the positions of these nearby steady states and their basins of attraction would be far more important from a safety point of view than testing for instability at the upright zero-rate-of-turn position, which is a commonly occurring and rather harmless phenomenon for operating ships.

3. THE MATHEMATICAL MODEL

A non-linear mathematical model with four degrees of freedom, is considered as outlined below:

$$\begin{aligned}
&\text{surge}: && m(\dot u - rv - x_G r^2 + z_G pr) && = X_H + X_P + X_R \\
&\text{sway}: && m(\dot v + ru + x_G \dot r - z_G \dot p) && = Y_H + Y_P + Y_R \\
&\text{yaw}: && I_Z \dot r + m x_G (\dot v + ru) && = N_H + N_P + N_R \\
&\text{roll}: && I_X \dot p - m z_G (\dot v + ru) && = K_H + K_P + K_R
\end{aligned} \tag{1}$$

The hull forces and moments are calculated as follows:

$$\begin{aligned}
X_H &= X_{\dot u}\dot u - Y_{\dot v} vr - (u/|u|) Y_{\dot r} r^2 + X_{vr} vr - \mathrm{Res}(u) \\
Y_H &= Y_{\dot v}\dot v + Y_{\dot r}\dot r + Y_v vU + (u/|u|) Y_r rU + Y_{v|v|} v|v| + Y_{v|r|} vr + \\
&\quad + (u/|u|) Y_{r|r|} r|r| \\
N_H &= N_{\dot r}\dot r + N_{\dot v}\dot v + N_r rU + (u/|u|) N_v vU + N_{r|r|} r|r| + \\
&\quad + (u/|u|) N_{rrv} rrv/U + N_{vvr} vvr/U \\
K_H &= K_{\dot p}\ddot\phi + C(\dot\phi) + R(\varphi) - z_Y Y_H
\end{aligned} \tag{2}$$

The roll dependence of the sway force and yaw moment was taken into account up to the first order by including in the right-hand side of the sway and yaw equations the terms:

$$\begin{aligned}
Y_{H\phi} &= Y_\phi \phi + Y_{v|\phi|} v|\phi| + Y_{r|\phi|} r|\phi| \\
N_{H\phi} &= N_\phi \phi + N_{v|\phi|} v|\phi| + N_{r|\phi|} r|\phi|
\end{aligned} \tag{3}$$

where, for example $Y_{v|\phi|} = Y_v(\phi) - Y_v(0)$, with the dependence of $Y_v(\phi)$ derived from **(6)**.

The roll damping $C(\dot\phi)$ is calculated as suggested in **(9)**, while the restoring moment is derived from the hull sections at various heeling angles with a seventh order polynomial being fitted to the results. The effects of trim and shallow water on the hydrodynamic coefficients were taken from **(10)** and **(11)** respectively.

The thrust generated by the propeller is given by

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

$$K_T = c_0 + c_1 J_P + c_2 J_P^2$$

The rudder forces and moments are modelled as suggested in **(6)**,

$$\begin{aligned}
X_R &= -F_N \sin\delta \\
Y_R &= -(1 + a_H) F_N \cos\delta \\
N_R &= -(1 + a_H (x_H/x_R))\, x_R F_N \cos\delta \\
K_R &= -(1 + a_H)\, z_R F_N \cos\delta
\end{aligned}$$

The rudder-to-hull interaction factor a_H appearing in the above expressions was calculated as a function of the relative position of the rudder to the hull, as explained in **(12)**.

4. STABILITY ANALYSIS

After undergoing a number of transformations, the motion equations are brought into the dynamical systems form:

$$\dot{\mathbf{z}} = \mathbf{F}(\mathbf{z}, \mathbf{a}) \tag{4}$$

where $\mathbf{z}$ is the vector of the state variables of the system $z = (u, v, r, p, \varphi)^T$ and $\mathbf{a}$ is a control parameter, whose effect on the system's behaviour is investigated. This can be selected to be any of the rudder angle, propeller rate, trim or water depth.

Equation (4) is used to investigate either the transient response of the system to changes taking place in its control space, or to analyse long-term behaviour by identifying the dependence of its steady states on a varying control parameter. The latter requires the tracing of sequences of points of static equilibrium by deriving the dependence $z(a)$ from the equation

$$F(z(a), a) = 0$$

This is achieved automatically and quickly by differentiating equation (5) with respect to a parameter ℓ accounting for the length of the solution curve, followed by a transformation into an initial values integration problem. The procedure is described in detail in **(13)**.

An important feature of the algorithm is that it contains a stability analysis routine so that in the vicinity of each steady state identified, local linearisation is performed, by substituting $\mathbf{z} = \mathbf{z}_0 + \mathbf{b}$ into (4), where $\mathbf{b}$ represents the vector of deviations from $\mathbf{z}_0$, yielding

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

where $\mathbf{C}$ is the Jacobian matrix of $\mathbf{F}$. The criterion then for instability is the existence of positive real parts in the eigenvalues of **C** .

5. APPLICATIONS

5.1 A Wide-Beam River Boat

The procedure described above was applied initially to a wide-beam river boat, see Table 2, which had been reported as having capsized even though its metacentric height was significantly high. The analysis results, which were detailed in **(14)** and are summarised in Table 1, indicated clearly that bow trim could have caused almost complete loss of control, since the instability region would have grown to the extent of occupying most of the control space of the system (see Fig. 2).

Furthermore, because of the dynamic instability of the ship at the upright position, relatively large steady heeling angles (and therefore even larger transient heel) could well occur at around zero rudder setting, for a vessel whose down-flooding angle was only 12°. This means that even in the absence of any control action or other "internal" or "external" effects, dangerous inclinations could have been experienced, as a result of instantaneous or permanent trim by the bow, when the system would be seeking a distantly located equilibrium. It was further noticed that by reducing the metacentric height, GM, (which meant increase of the roll effects on the horizontal motions) the instability would increase too, in terms of both the loop-height and the loop-width of the spiral curves of Fig. 2.

5.2 The HERALD OF FREE ENTERPRISE

The above findings led to the consideration of the **HERALD OF FREE ENTERPRISE** disaster, where bow trim was also suspected of having played a key role in the capsizing phenomenon, **(2)** and **(7)**. The results of an investigation along the above lines for this vessel (whose particulars are summarised in Table 3) are presented next:

a) Effect of trim by bow

The conditions examined are:

- even keel
- 0.5m trim by bow (0.227°)
- 1.0m trim by bow (0.454°).

Figs. 3 and 4 show that even at the upper limit of "normal" operational conditions, if GM was maintained high (1.64m), no significant heel or instability could occur (maximum heel angle 3.15°, maximum loop-width 5°). For comparison purposes, the somewhat unrealistic condition of 2.2m trim, which requires an extrapolation from the valid range of trim-correction coefficients, is included also in Fig. 3. Trim by bow would not seriously affect maximum heel because of the existence of near fore-, aft-, symmetry, rendering the statical stability curve practically insensitive to trim.

b) The effect of reduced metacentric height

It was noticed that, by reducing GM down to 0.5m, transient heeling could exceed 10° while the stable steady states corresponding to the "rudder amidships" condition would keep aloof from the axes origin (see Figs. 5 and 6).

c) The effect of shallow water

Fig. 7 shows the effect of shallow water with or without inclusion of the sinkage and trim known to occur during operation in shallow water. The trend is towards reduced instability at smaller water-depth to draught ratios.

5.3 A Proposal for the most Likely Capsize Scenario

The above results do not provide enough evidence to establish that trim by bow within the normal operational range could represent a threat, even if the dynamic water elevation around the bow was taken into account as a bow trim-like effect. It is much more likely that considerable dynamic instability was incurred only once water began to coming in through the bow doors, because of the significant extra trim induced by the incoming water.

However, to model and simulate behaviour for these specific circumstances has not been feasible because of the limited data available. Water ingress was facilitated by the fact that at the critical moment the vessel was operating in shallow water at a relatively high speed, as the height of the bow wave was found to be sensitive to the two aforementioned factors, **(2)**. Once water started accumulating inside the deck the ship would experience a marked growth of instability which would cause it to initiate a turn with her rudders practically unable to restore control over the developing situation. A turn to starboard would induce a small heel to port (the outer side of the turning circle) which could be enough to provide the initial heel necessary to allow the water inside the deck to start concentrating on one side of the ship. This would inevitably create a vicious circle with the additional water causing extra heel, which would affect motion on the horizontal plane by inducing a tighter turn, leading to greater heel.

A simplistic model of progressive flooding was adopted for illustration purposes and the simulation results are presented in Fig. 8, providing some proof for the claim made here. This interesting phenomenon of the interplay between roll and planar motions accelerating the capsizing, is currently under investigation and, given time and resources, results will be available soon for publication.

The effect of transient flooding in the simplified case of no forward speed, and ignoring of the above mechanism, is shown in Fig. 9, (15). The graph is the result of time-simulation based on a sway-heave-roll mathematical model and it is possible to see that for KG = 11.0m, it would take just over two minutes for the ship to capsize (with a steady water ingress of $4m^3/sec$ and a 0.45° trim by the bow.)

6. CONCLUDING REMARKS

Based on the results of the foregoing investigations, the following remarks can be made:

a) A new approach has been proposed for studying the interplay between directional and transverse stabilities which can be extended to include the effect of waves. The authors believe this will provide a means for effectively addressing the problem of broaching-to.

b) Especially in vessels operating at high length/draught ratios, bow trim can generate almost complete loss of control, corrective action for which could lead to excessive heeling. For vessels operating at relatively low length/draught ratios, (e.g., the HERALD OF FREE ENTERPRISE), the influence of bow trim on controllability is much reduced.

c) The operational bow trim alone was not the key to the capsize of the HERALD OF FREE ENTERPRISE; i.e., if the bow doors had been closed the vessel would not have capsized. Ingress of water through the bow doors resulted in increased trim and led to the loss of control, causing the vessel to turn and hence gave rise to an initial heel. This heel aggravated the rate of turn and vice versa until the vessel capsized.

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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ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support of the University of Strathclyde. They would also like to express their thanks to Mr O Turan for preparing Fig. 9 and to Miss Christine Hutcheon for her valued assistance in the preparation of this paper.

TABLE 1: PARAMETRIC INVESTIGATION OF THE WIDE-BEAM RIVER BOAT

EFFECT OF TRIM BY THE BOW			EFFECT OF GM (Loading dependent)			EFFECT OF FORWARD SPEED			
GM = 2.0m Vs = 10.0 Kn			Trim = 0.4m Vs = 10.0 Kn			Trim = 1.0m GM = 2.0m			
Trim	Loop Halfwidth	Transient Heel	GM	Loop Halfwidth	Transient Heel	Speed	Loop Halfwidth	Speed	Transient Heel
0.0m	1.2°	3.0°	2.0m	7.0°	5.1°	4.0kn	19.0°	6.0kn	2.1°
0.4m	7.0°	3.8°	1.0m	8.0°	7.2°	9.0kn	18.2°	10.0kn	3.1°
1.0m	17.0°	4.5°	0.5m	10.0°	20.0°	10.3kn	17.0°	12.2kn	5.0°

TABLE 2: WIDE BEAM RIVER BOAT MAIN DIMENSIONS

Length	L(m)	=	37.45
Beam	B(m)	=	7.93
Draught	T(m)	=	1.52
Block Coefficient	C_b	=	0.632
Service Speed	$V_{s(kn)}$	=	10
Downflooding Angle		=	12°

TABLE 3: HERALD OF FREE ENTERPRISE MAIN DIMENSIONS

Length	L(m)	=	126.1
Beam	B(m)	=	22.7
Draught	T(m)	=	5.7
Block Coefficient	C_b	=	0.525
$\frac{\text{Main Rudder Area}}{\text{Length-Beam}}$	$A_R/(LT)$	=	0.0238
Simulation Speed		=	16 Knots

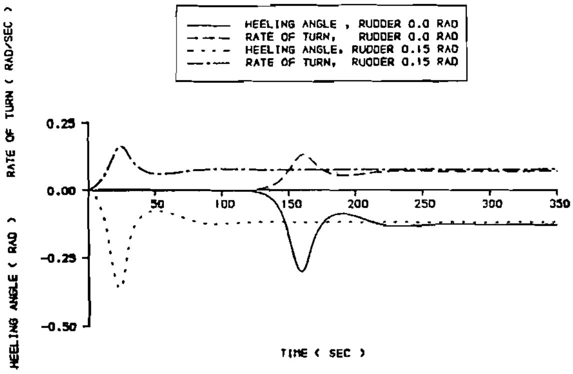

Fig. 1: Convergence to nearby stable states

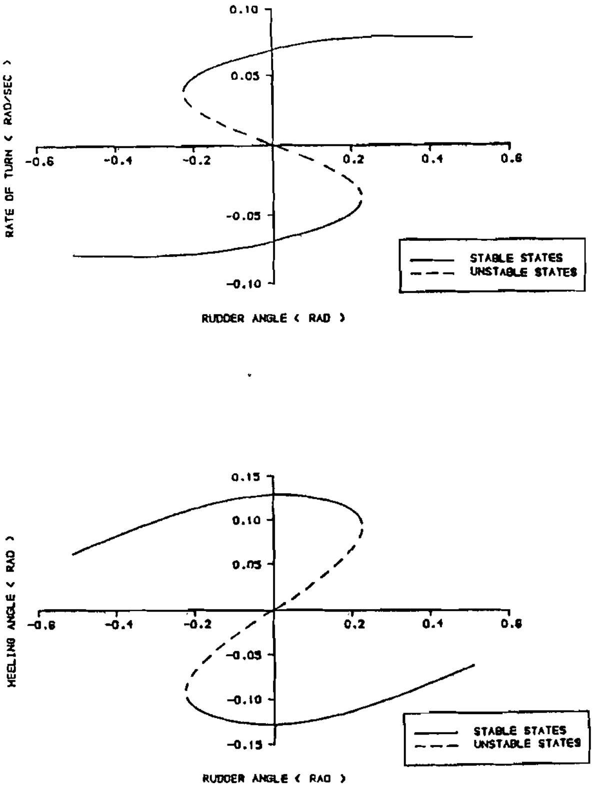

Fig. 2: Regions of instability

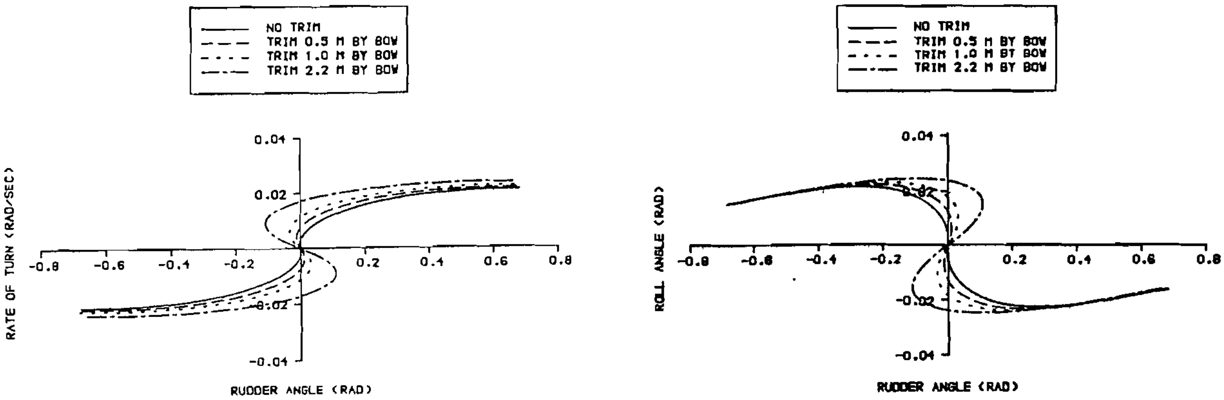

Fig. 3: Effect of trim by the bow: steady states

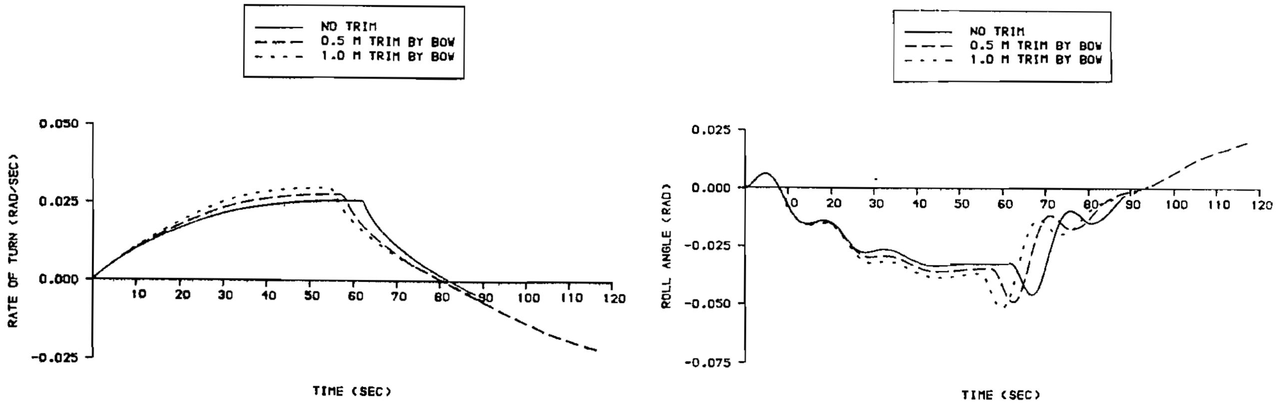

Fig. 4: Effect of trim by the bow: yaw checking manoeuvres

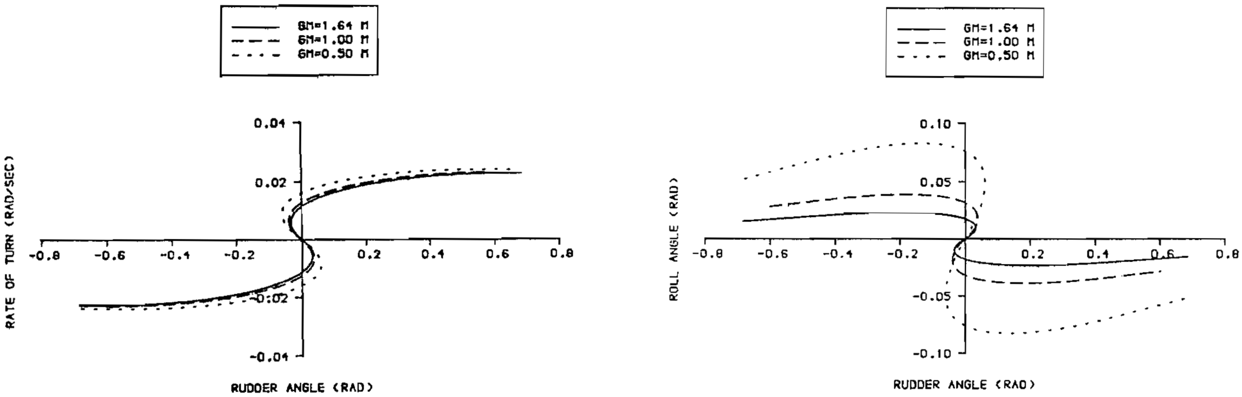

Fig. 5: Effect of GM on steady states, trim 1.0m by the bow

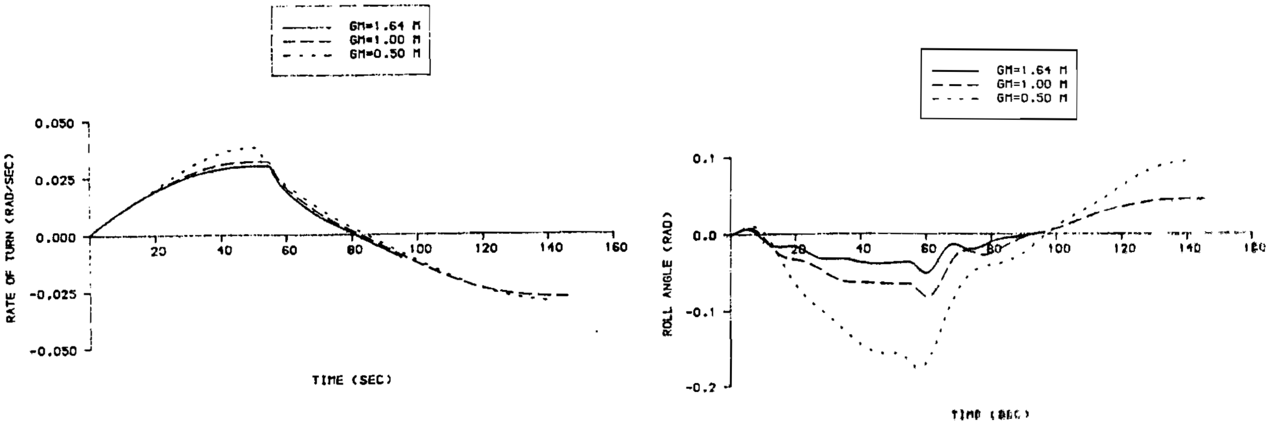

Fig. 6: Effect of GM on yaw checking manoeuvres, trim 1.0m by the bow

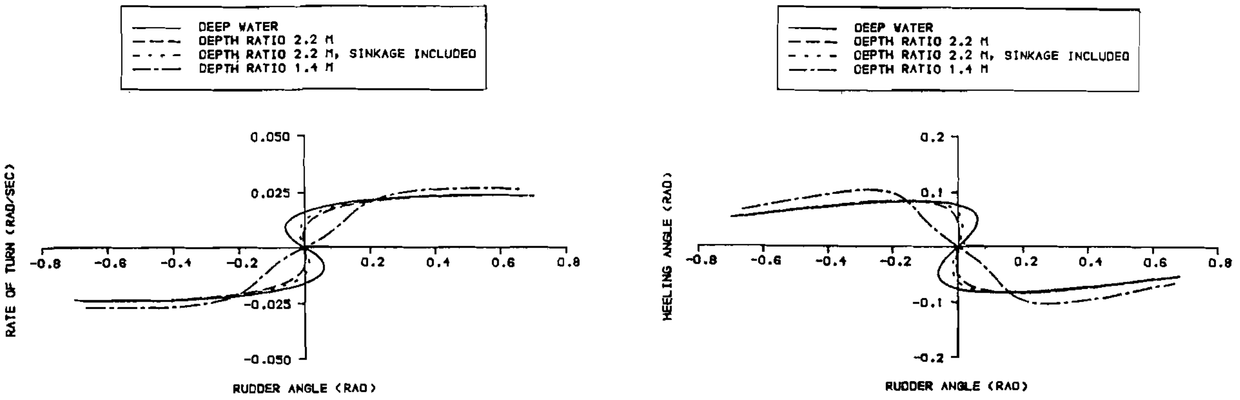

Fig. 7: The shallow water effect

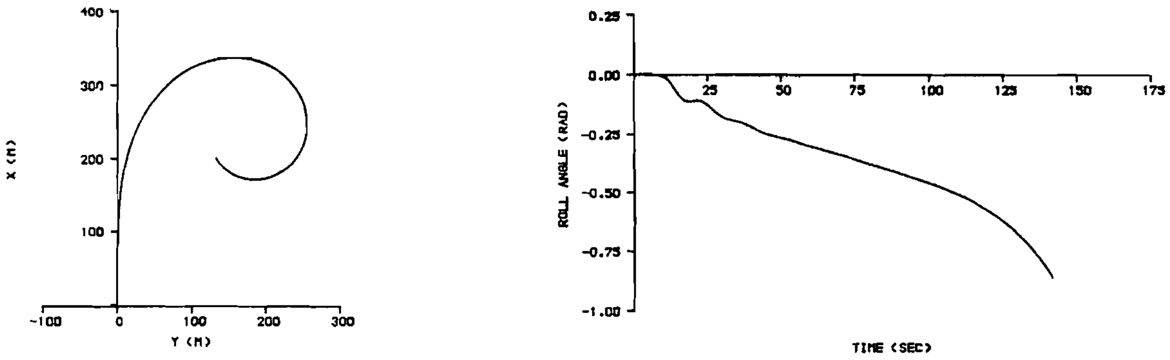

Fig. 8: Increasing turning and heeling leading to capsize

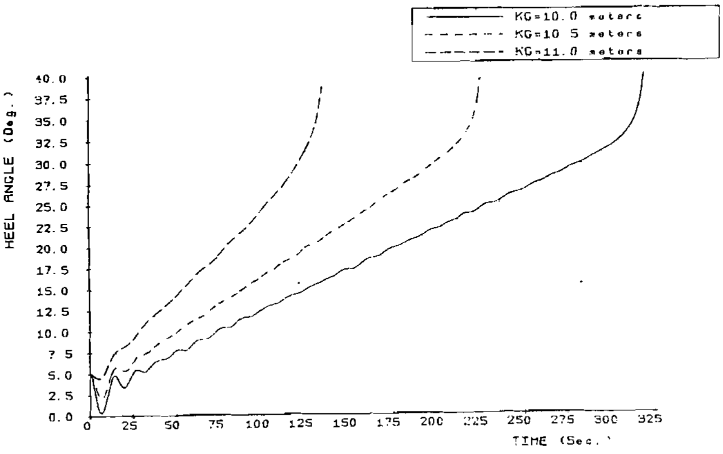

Fig. 9: Progressive flooding of HERALD water ingress rate: $4m^3/s$ (KG = 11.0m corresponding to GM = 0.92m)