AN INVESTIGATION INTO THE PRINCIPLE CAUSES OF SHIPS BROACHING-TO IN FOLLOWING SEAS

by M.R. RENILSON [1]

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INTRODUCTION

When a ship is travelling at a certain speed in a following sea of a certain length and steepness it can suddenly be picked up on the face of a wave and yawed violently through up to 90 degrees despite application of full opposite rudder. This phenomenum is known as broaching-to and in addition to being very frightening to those on board can cause considerable damage and possibly even a capsize.

In order to investigate this the Admiralty Marine Technology Establishment (AMTE) carried out some free running model experiments in regular waves.(1) Plots of typical path records from those experiments are given in figure 1 taken from ref. 1. On analysing the results it was possible to plot the boundaries of the broaching zone on a graph of non dimensional wavelength against froude number as shown in figure 2. This was repeated for a number of wave steepnesses, GM values, rudder sizes and hull forms, however, although a qualitative impression of how a ship broached was gained it was not possible to identify the way in which the various factors influenced the behaviour. In order to do this a more theoretical approach was required and it was decided to set up a simulation which would enable the forces and moments involved to be quantified.

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1. Lecturer, Australian Maritime College

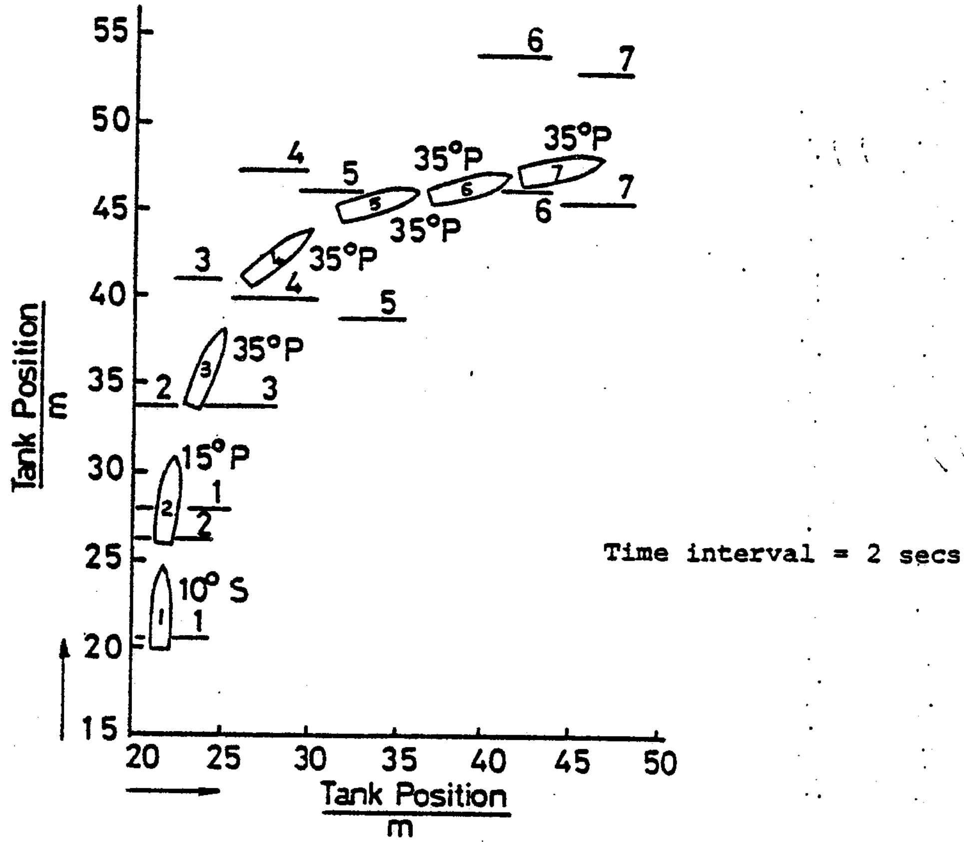

Figure 1. Plot of broached run (taken from Ref. 1.)

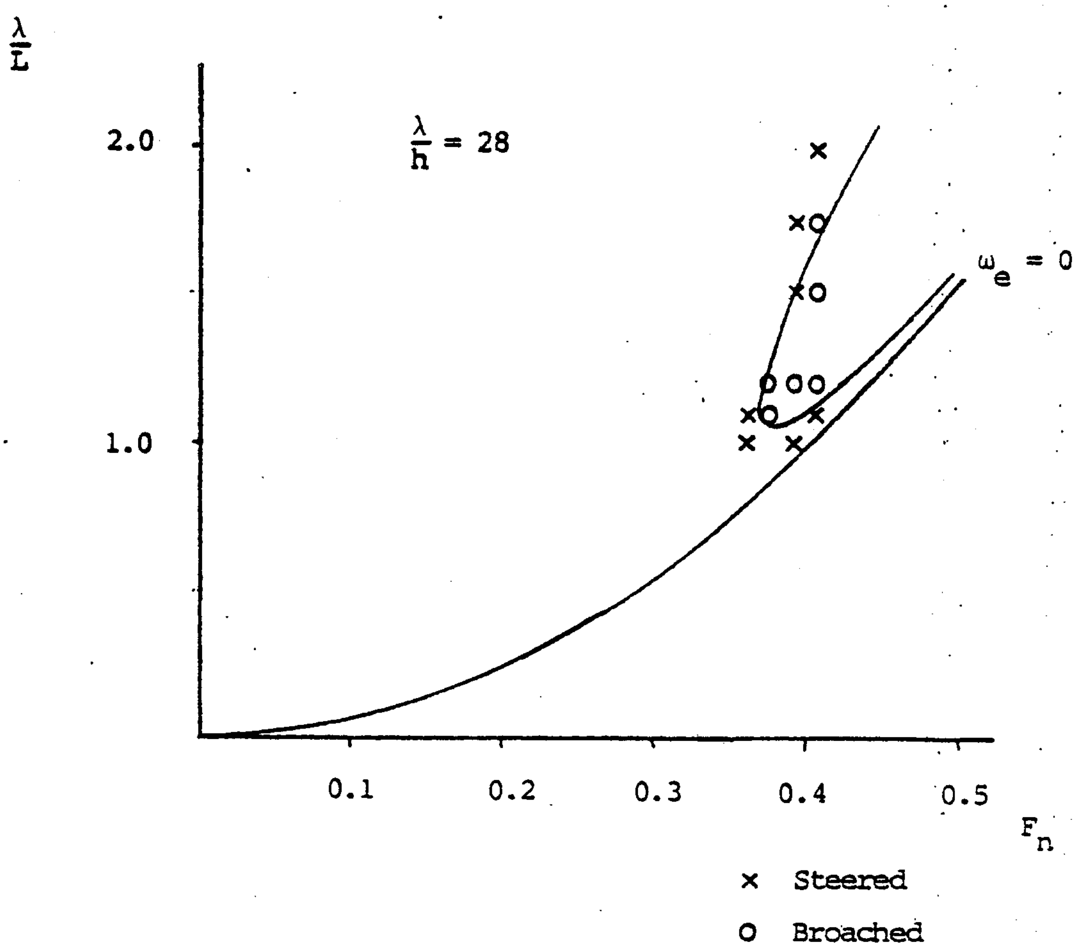

Figure 2. Broaching zone for standard rudder
(From an unpublished report by Lloyd)

MATHEMATICAL MODEL

The first step in setting up the simulation was to devise a mathematical model. It was decided to base this on the linear manoeuvring equations which have been used over the years for calm water manoeuvring and are well understood. The rational for using linear equations to simulate a highly non linear phenomenom was that the intention was only to predict whether or not a ship would broach under a given set of conditions and what the relative contributions for the various factors were. It was not intended to plot the exact path or to obtain the exact forces and moments at any point in time. Certain non linearities were added to the equations when it was felt they were important.

The standard linear equations of motion for manoeuvring are:

$$Y'_v v' + (Y'_{\dot v} - m')\dot v' + (Y'_r - m')r' + (Y'_{\dot r} - m'x'_G)\dot r' + Y'_\delta \delta' = 0 \quad (1)$$

$$N'_v v' + (N'_{\dot v} - m'x'_G)\dot v' + (N'_r - m'x'_G)r' + (N'_{\dot r} - I'_z)\dot r' + N'_\delta \delta' = 0 \quad (2)$$

Now, the various hydrodynamic coefficients (or derivatives) such as Yv, Yr, $Y\dot v$ .... etc. are all dependent on the form of the wetted part of the hull. As can be seen from figure 3 when the ship is in a steep wave this can change significantly and thus it is reasonable to assume that these coefficients are not constant but vary as functions of the relative position of the wave and the ship.(5)

Two important observations can be made from studying the AMTE broaching records:

(1) When a broach occurs the model speed is very close to wave speed

(2) The model speed varies significantly.

The first of these indicates that the zero encounter frequency values can be assumed for the coefficients. This is quite important because what it means is that the coefficients can be obtained by poising the hull statically on the wave.

The second observation confirms that made by Du Cane and Goodrich (2) when they studied surging and broaching in a following sea. It indicates that the wave imposes a considerable longitudinal force on the hull and therefore it cannot simply be assumed to be overtaking the ship at a constant relative

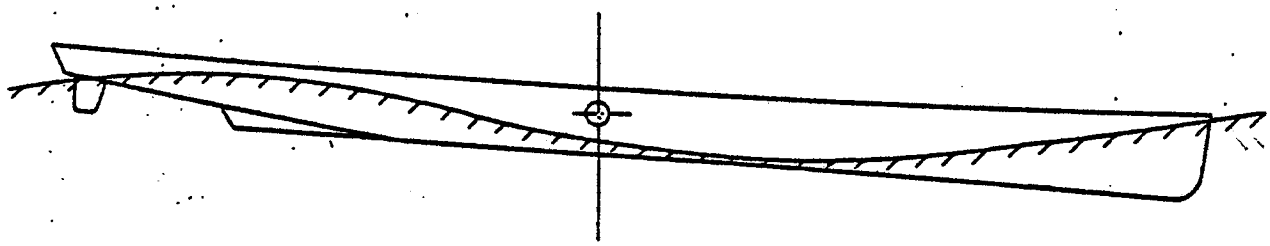

Figure 3 Profile Of The Hull In A Wave

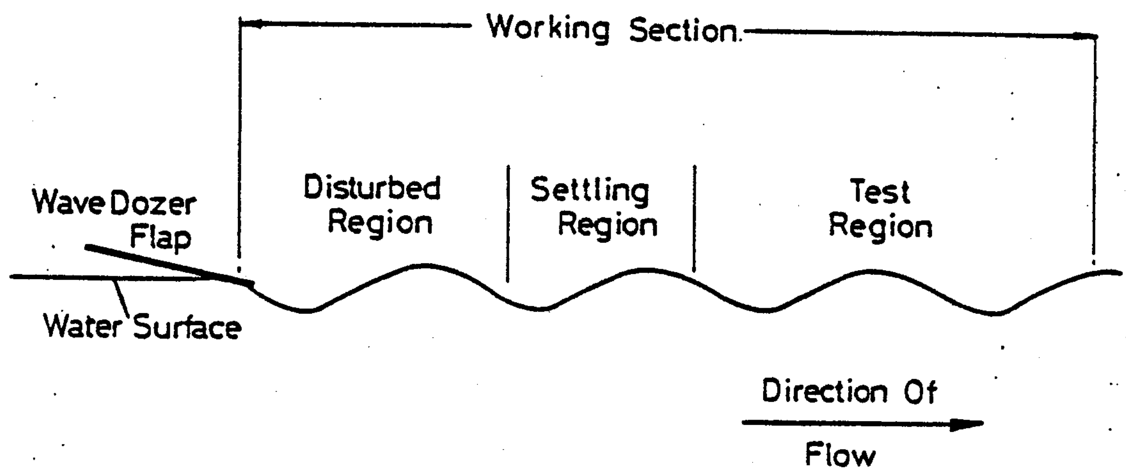

Figure 4 Schematic Diagram Of Experiments In C.W.C

velocity. This means that the coefficients which are functions of ξ cannot be written in terms of time and that the longitudinal equation will be required.

It is well known that ships can heel considerably during the lead up to a broach. In order to decide whether the heel/yaw coupling was strong enough to require the heel equation to be included in the model, constrained experiments were carried out in calm water and the coefficients Y_ϕ and N_ϕ were obtained.(3) It was found that their value varied considerably with speed but that the yaw moment induced by the heel angles involved compared to that developed by a few degrees of rudder and hence that the heel equation could be neglected for the present purposes.

Finally, in addition to a longitudinal force the wave will impose a transverse force and a yawing moment on the hull which are both assumed to be directly proportional to heading angle and functions of ξ . When these terms and suitable equations for the autopilot are added the resulting model becomes:

$$0 = Y_v v + (Y_{\dot{v}} - m)\dot{v} + Y_\alpha \alpha + (Y_r - mU)\dot{\alpha} + Y_\delta \delta \quad (3)$$

$$0 = N_v v + N_\alpha \alpha + (N_r - mx_G U)\dot{\alpha} + (N_{\dot{r}} - I_z)\ddot{\alpha} + N_\delta \delta \quad (4)$$

$$0 = X_{u^2} U^2 + (X_{\dot{u}} - m)\dot{u} + X_\xi + X_{prop} + X_\delta |\delta| \quad (5)$$

$$\xi = \frac{1}{\lambda} \int_0^t [U - C - v\alpha]\, dt \quad (6)$$

$$\delta_d = P_1 \psi + P_2 \dot{\psi} \quad (7)$$

$$\delta_a = \int_0^t \dot{\delta}_a \, dt \quad (8)$$

$$-C_3 < \dot{\delta}_a < C_3 \quad (9)$$

$$-\delta_{a_m} < \delta_a < \delta_{a_m} \quad (10)$$

THE COEFFICIENTS

Once the model had been set up the next stage was to obtain the coefficients. Basically there are two ways to do this:

(1) Using captive model experiments

(2) From theory

Captive model experiments

The only way to obtain the required coefficients in a conventional towing tank was to use a Planar Motion Mechanism (PMM). This oscillates a model in the desired mode over a range of frequencies and amplitudes and the results are analysed to obtain the so called slow motion derivatives. Ref. 4 describes the conventional analysis technique. The problem of testing with the PMM in the following sea condition was that of obtaining the situation when the model is travelling at exactly the same speed as the wave. If this condition was not achieved then part of the lateral oscillation of the model would be at one longitudinal wave position and part at another. In other words in addition to varying v and $\dot{v}$ (r and $\dot{r}$)with time, ζ would be varying too making subsequent analysis impossible.

The way this was overcome was to use a moving flap, or wavedozer, which creates a train of waves in its wake, all travelling at exactly the same speed as the flap. This technique was originally devised by Hogben (5) for creating large waves for use with offshore structures. Ref. 6 shows how this technique was adopted for the present requirement and how it was fitted in a large circulating water channel. (CWC).

Using the CWC had two principle advantages over a conventional tank for these experiments.

1) The wavedozer flap could be made a tight fit to the side of the channel wall making the resulting wave much cleaner and free of transverse disturbances.

2) The number of oscillations of the PMM were not restricted to those that could be carried out during the time it takes to reach the far end of the tank. This made the results from the PMM much more accurate.

In addition, it was easier to mount the wavedozer a considerable distance from the model (in order to reduce the possibility of wavemaker disturbances in the wave) it was easier to change the separation between the flap and the model (ζ) and the PMM results were not affected by a vibrating carriage as is the case when travelling at speed on even the smoothest of rails. Thus the experimental arrangement was as in fig. 4.

The experiments were carried out for a twin screw fine form model which had its freeboard increased to prevent swamping. Details of the model and the experimental technique together together with the modified analysis technique required to obtain all the coefficients for the modified mathematical model are given in ref. 7. Basically, the required coefficients were obtained first in calm water and then at seven different longitudinal positions in the wave, the seventh being a repeat of the first. The results were then plotted against wave position and compared with those obtained theoretically as can be seen in figures 5-18.

Theoretical prediction

A detailed description of the theoretical calculation of the coefficients is given in ref. 8. and it is not proposed to repeat this here. It is sufficient to say that calculation of the coefficients in calm water to any degree of accuracy is not possible at present due to cross flow drag, vortex shedding etc. These are not yet fully understood and they can have a significant effect on the lift and centre of lift of the hull which is acting as a very low aspect ratio lifting surface. For this reason a slightly alternative approach was used. The technique adopted for the velocity coefficients (Y_v, Y_r, N_v and N_r) was based on the assumption that the derivatives can be written as the sum of the potential flow and viscous flow components. It was further assumed that the presence of the wave will only affect the potential component and that this can be calculated from potential flow theory.

i.e. for the side force due to sway velocity :

$$Y_{v_{TOTAL}} = Y_{v_{POTENTIAL}} + Y_{v_{VISCOUS}}$$

As Yv_{TOTAL} can be found from experiments for calm water and $Yv_{POTENTIAL}$ can be calculated (for calm water) $Yv_{VISCOUS}$ can be obtained. Now, $Yv_{POTENTIAL}$ for the desired wave condition can be calculated and added to the constant value of $Yv_{VISCOUS}$ in the wave. This method does require knowledge of the velocity derivatives in calm water but these can be obtained using the conventional manoeuvring experiments.

The acceleration derivatives ($Y\dot{v}$, $Y\dot{r}$, $N\dot{v}$, and $N\dot{r}$) can be obtained using potential theory alone as can the coefficients relating heading to wave induced sway force and yawing moment (Y_α and N_α).

The rudder derivatives (Y_δ and N_δ) can be obtained using low aspect ratio lifting theory. Account must be taken of the possibility of the water surface coming

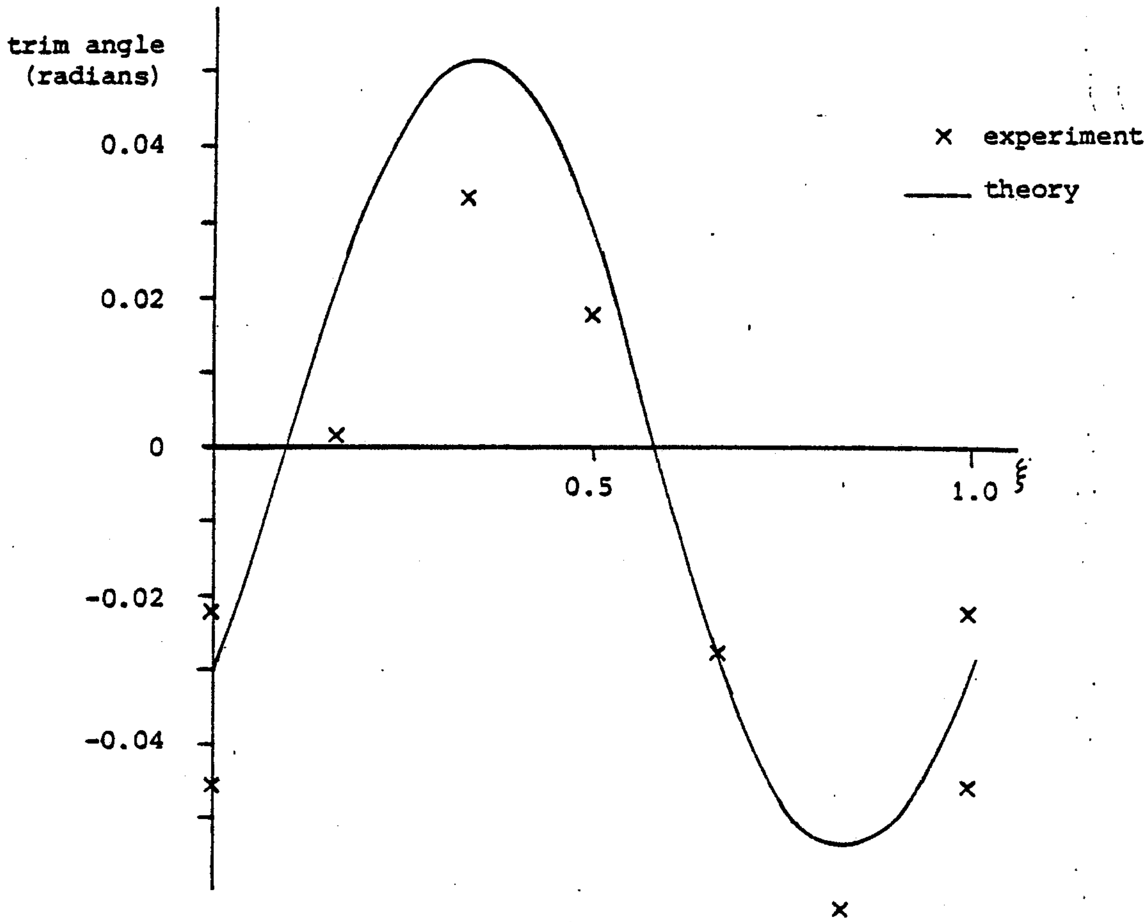

Figure 5. Trim as a function of ξ

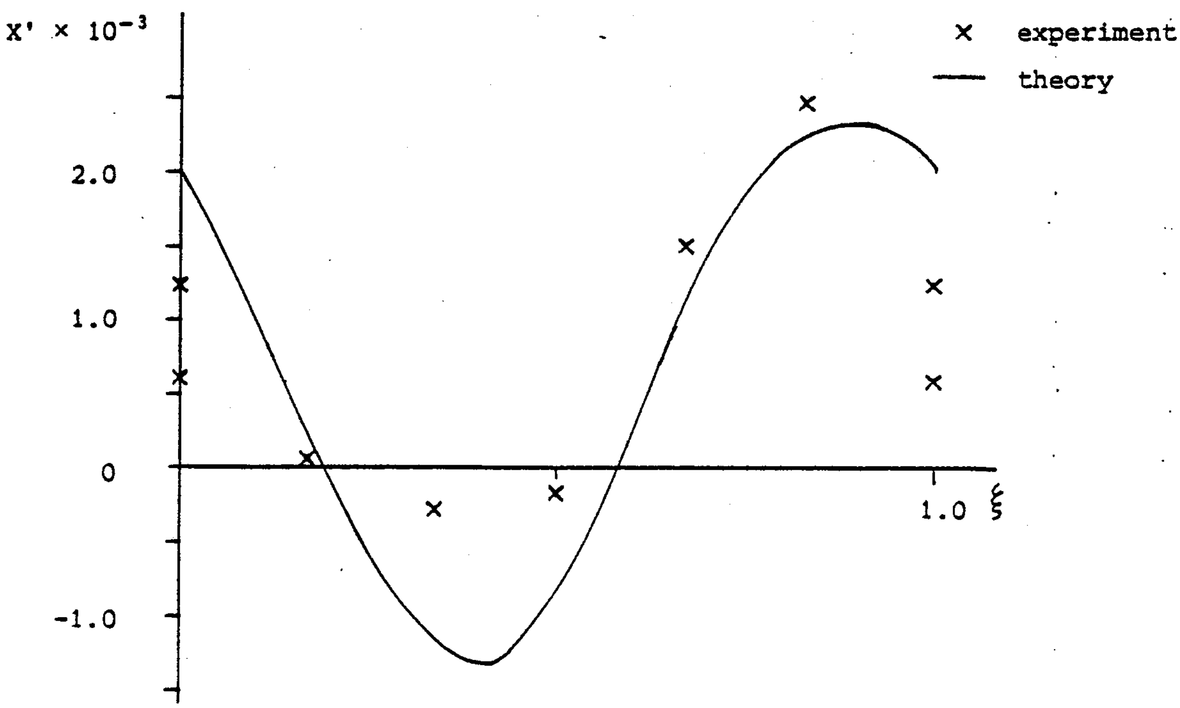

Figure 6. Non-dimensional X-force as a function of ξ

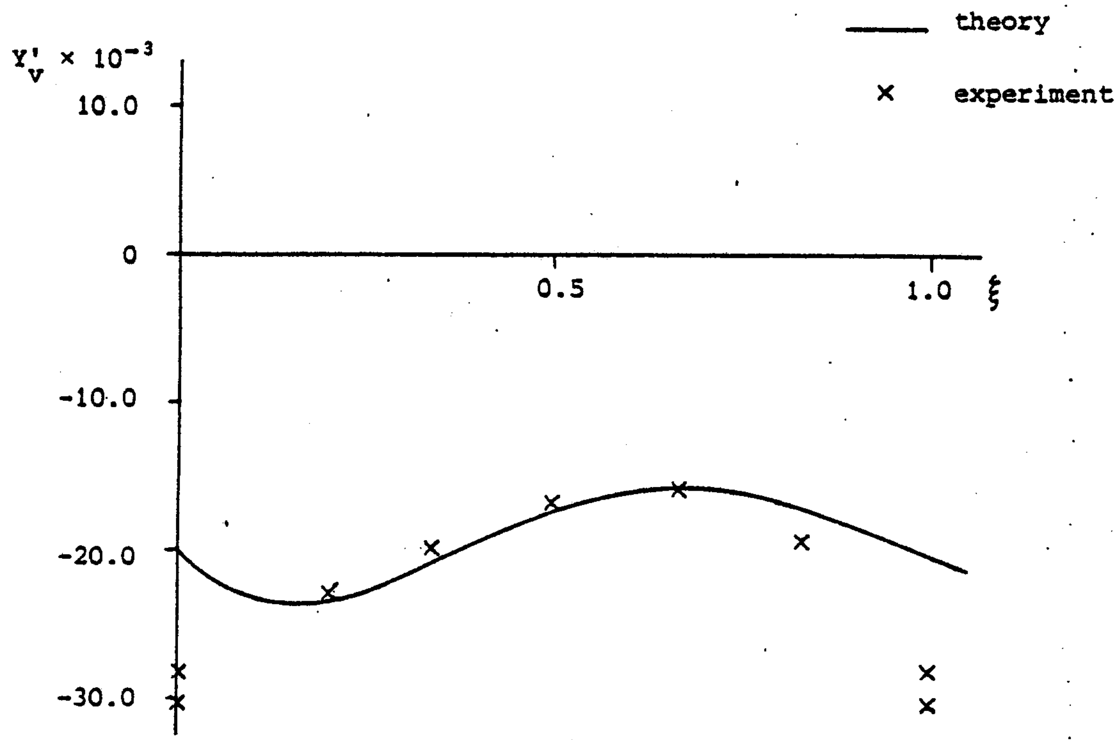

Figure 7. Y'_v as a function of ξ

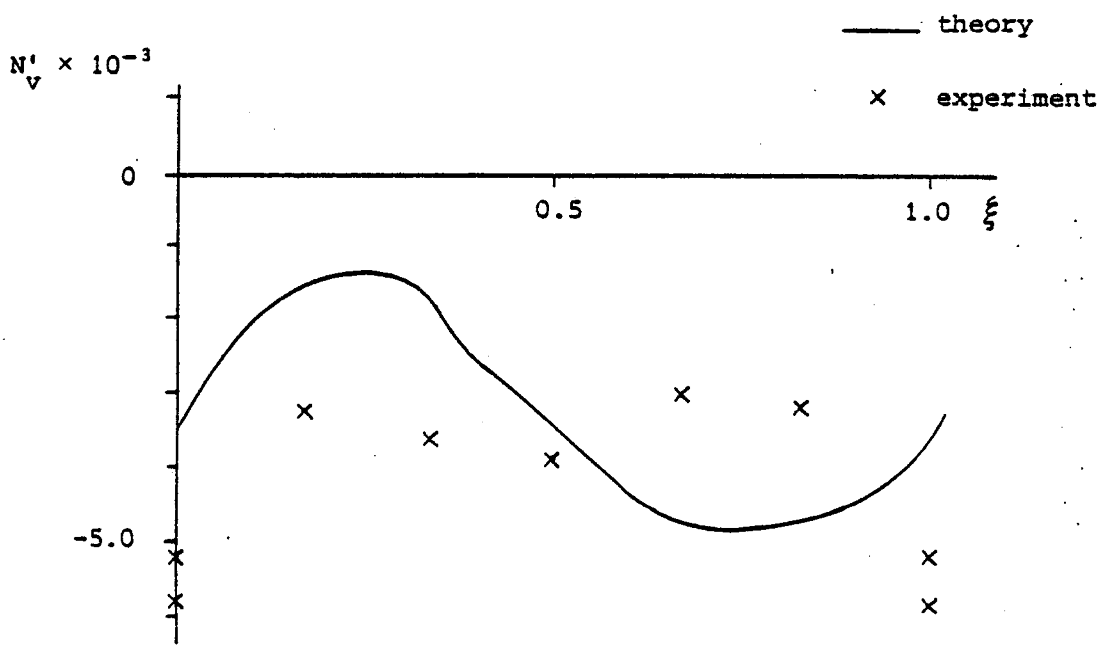

Figure 8. N'_v as a function of ξ

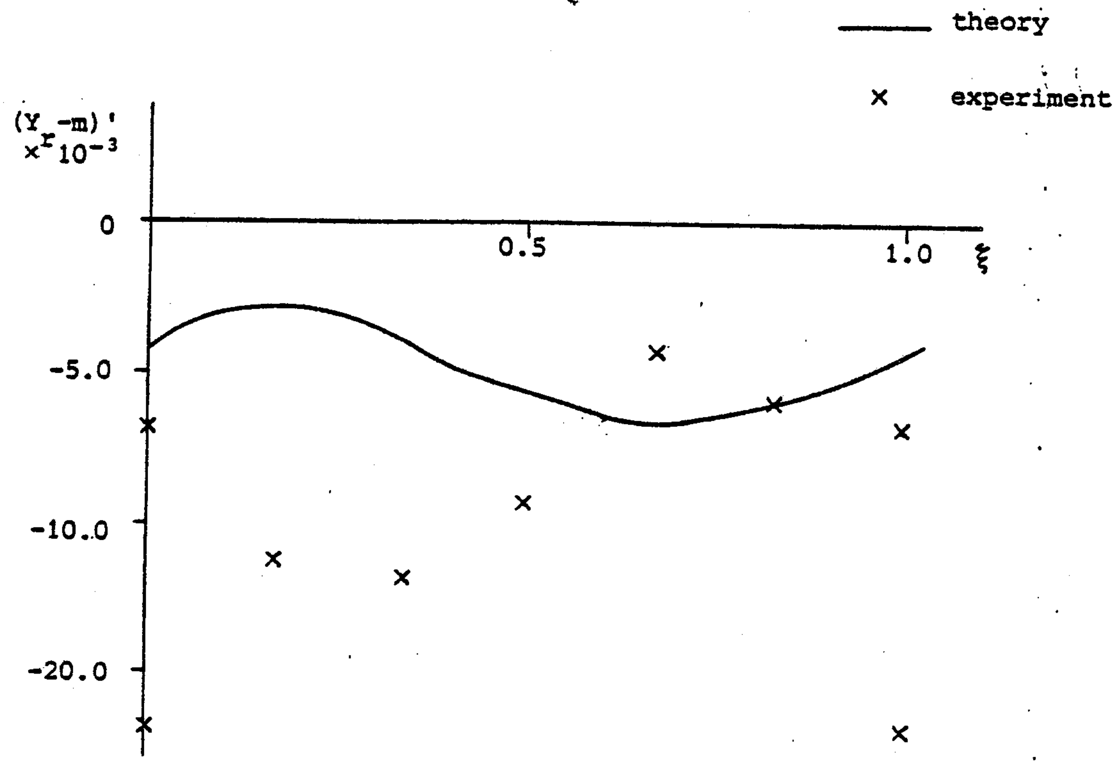

Figure 9. $(Y_r-m)'$ as a function of ξ

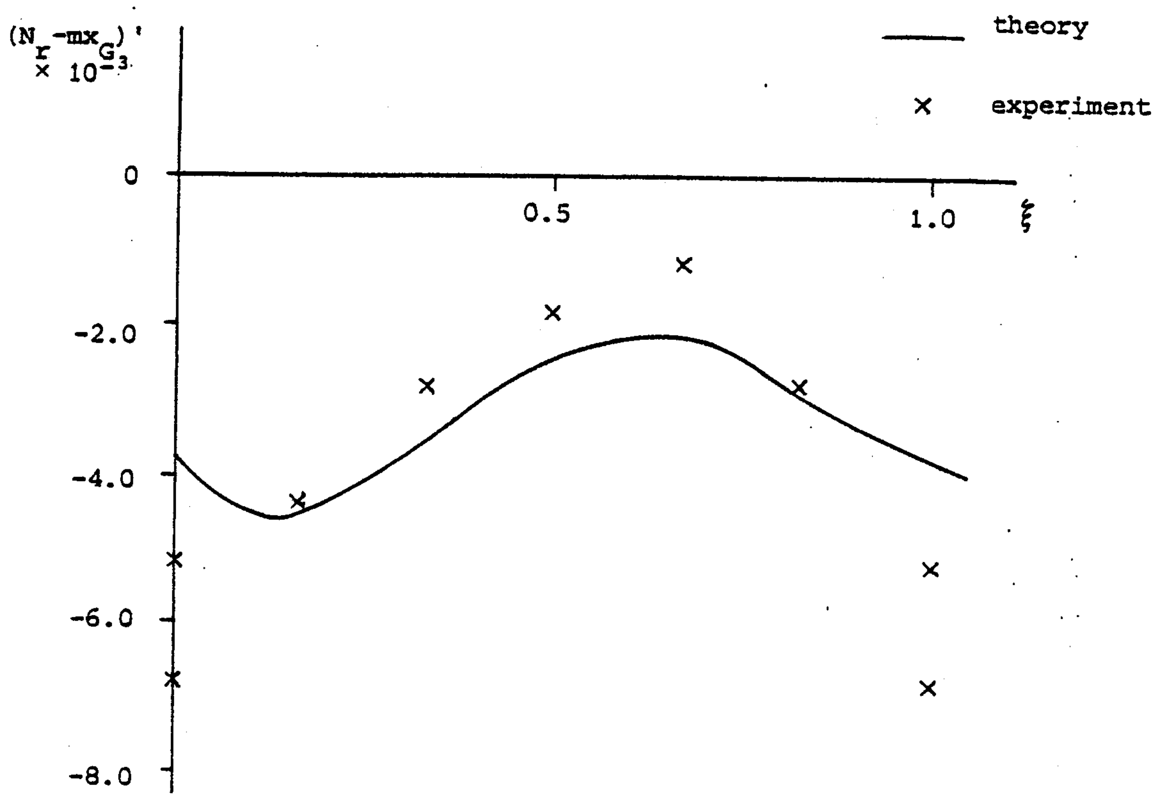

Figure 10. $(N_r-mx_G)'$ as a function of ξ

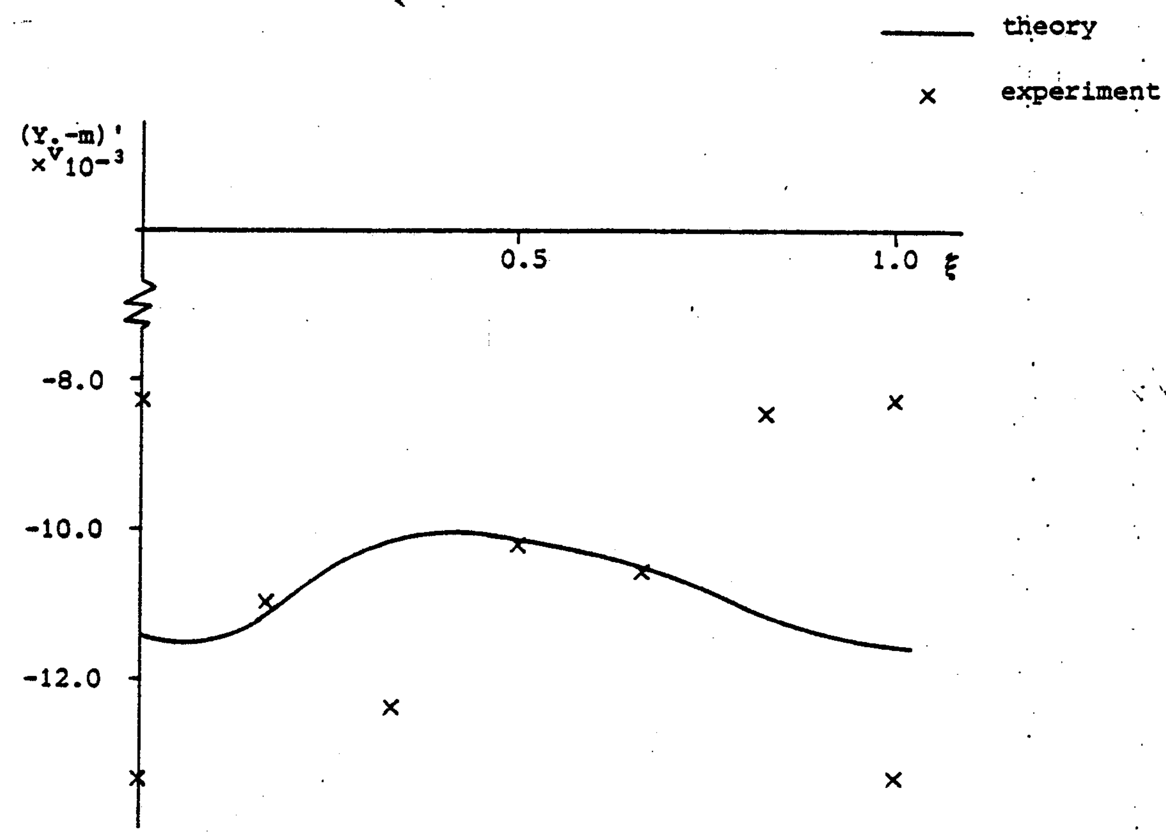

Figure 11. $(Y_{\dot{v}}-m)'$ as a function of ξ

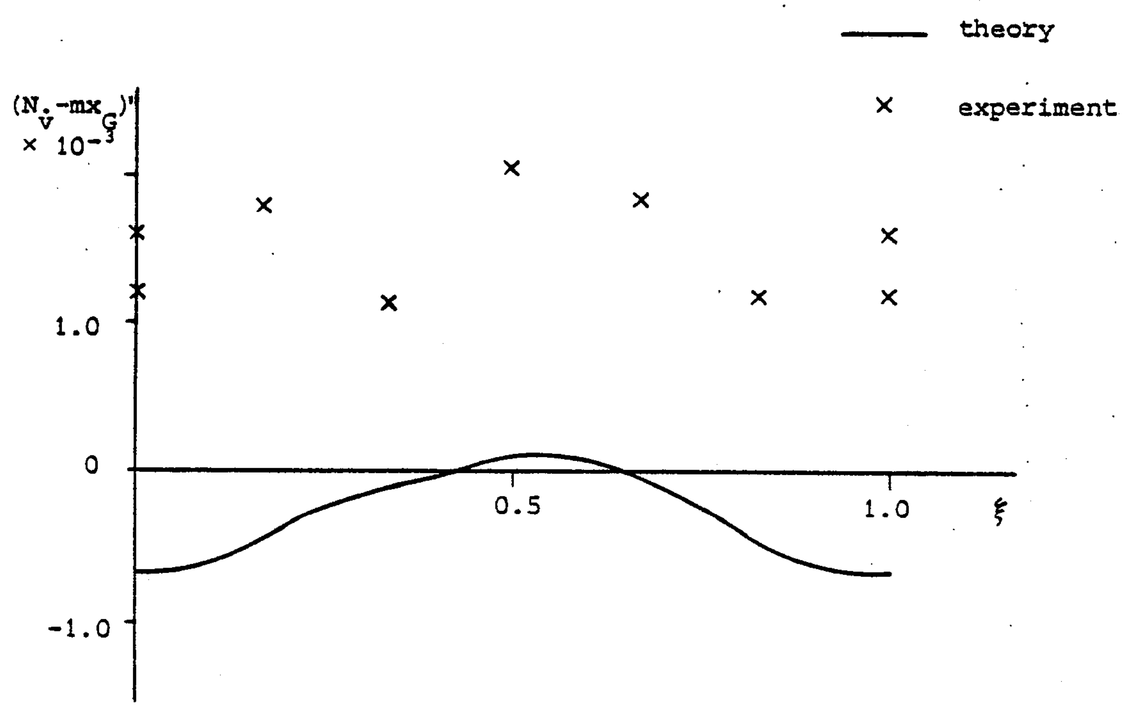

Figure 12. $(N_{\dot{v}}-mx_G)'$ as a function of ξ

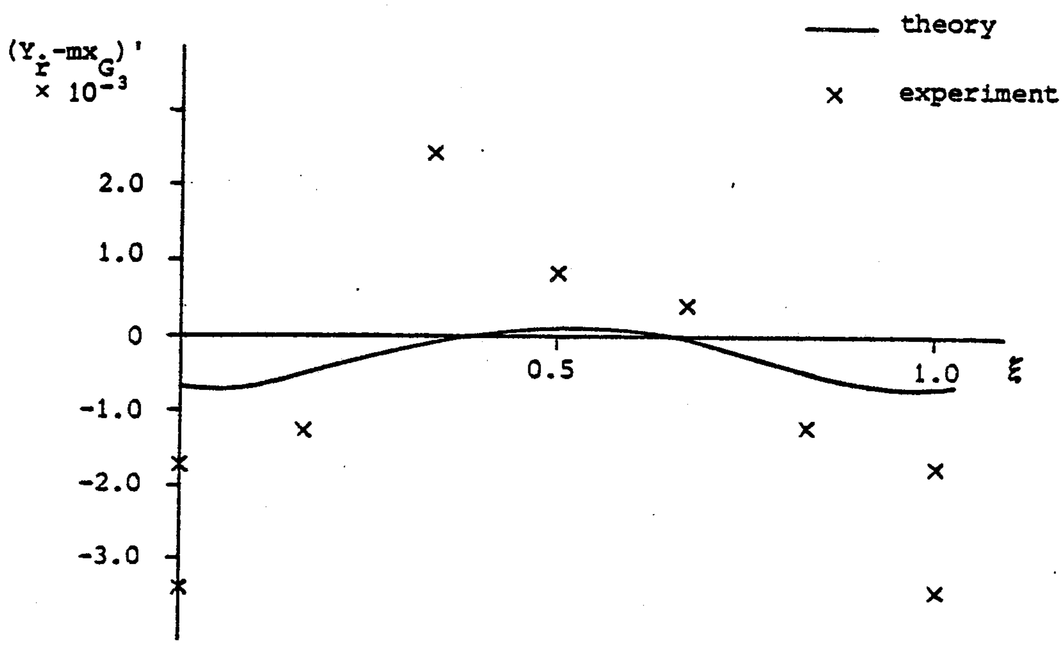

Figure 13. $(Y_{\dot{r}}-mx_G)'$ as a function of ξ

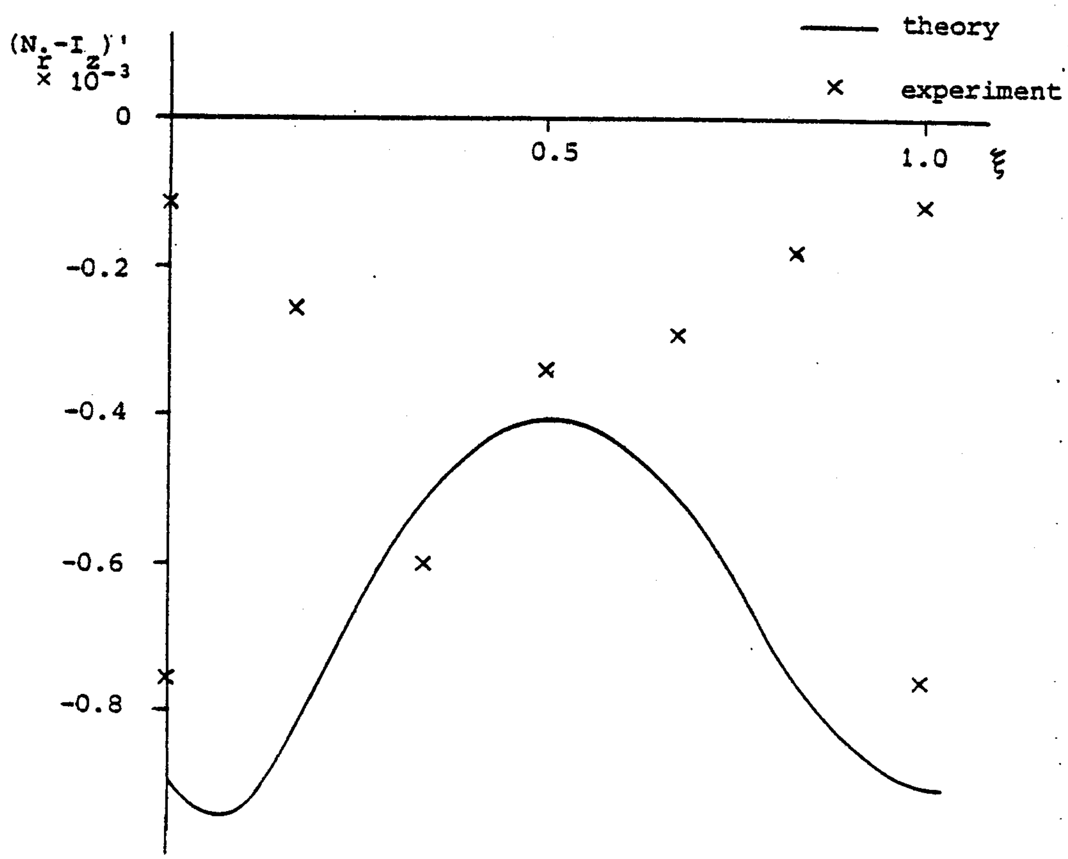

Figure 14. $(N_{\dot{r}}-I_z)'$ as a function of ξ

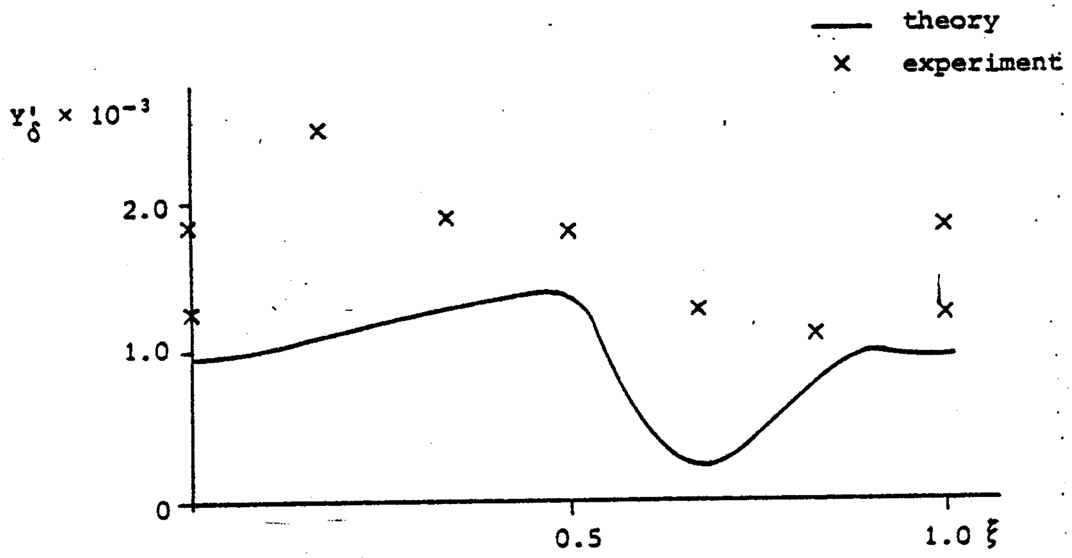

Figure 15. Y'_δ as a function of ξ

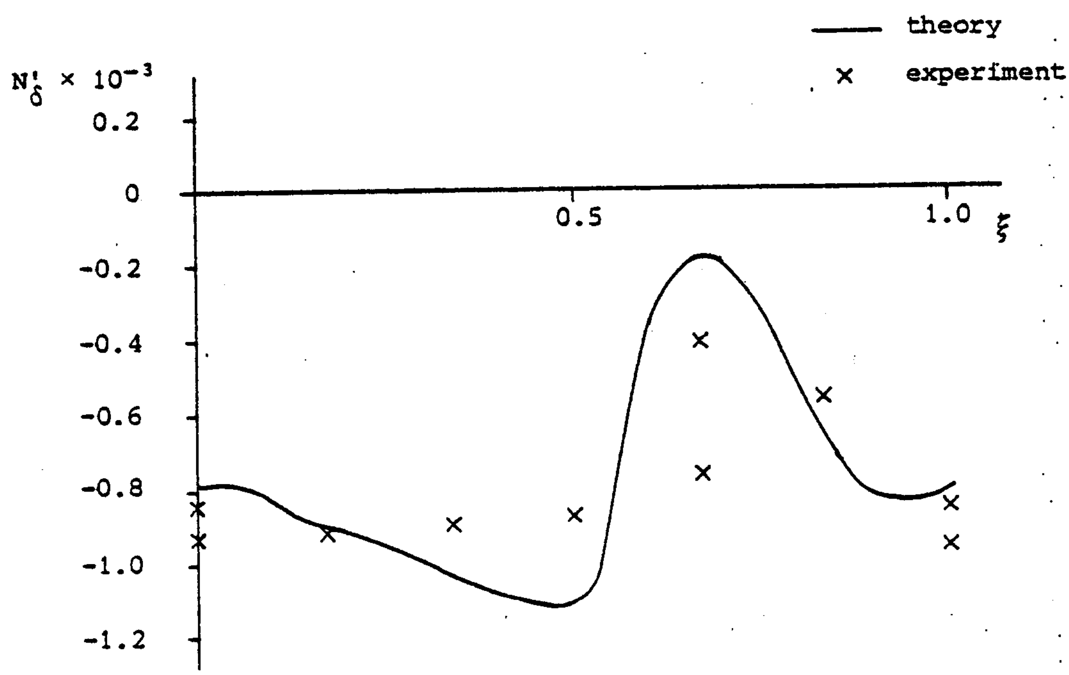

Figure 16. N'_δ as a function of ξ

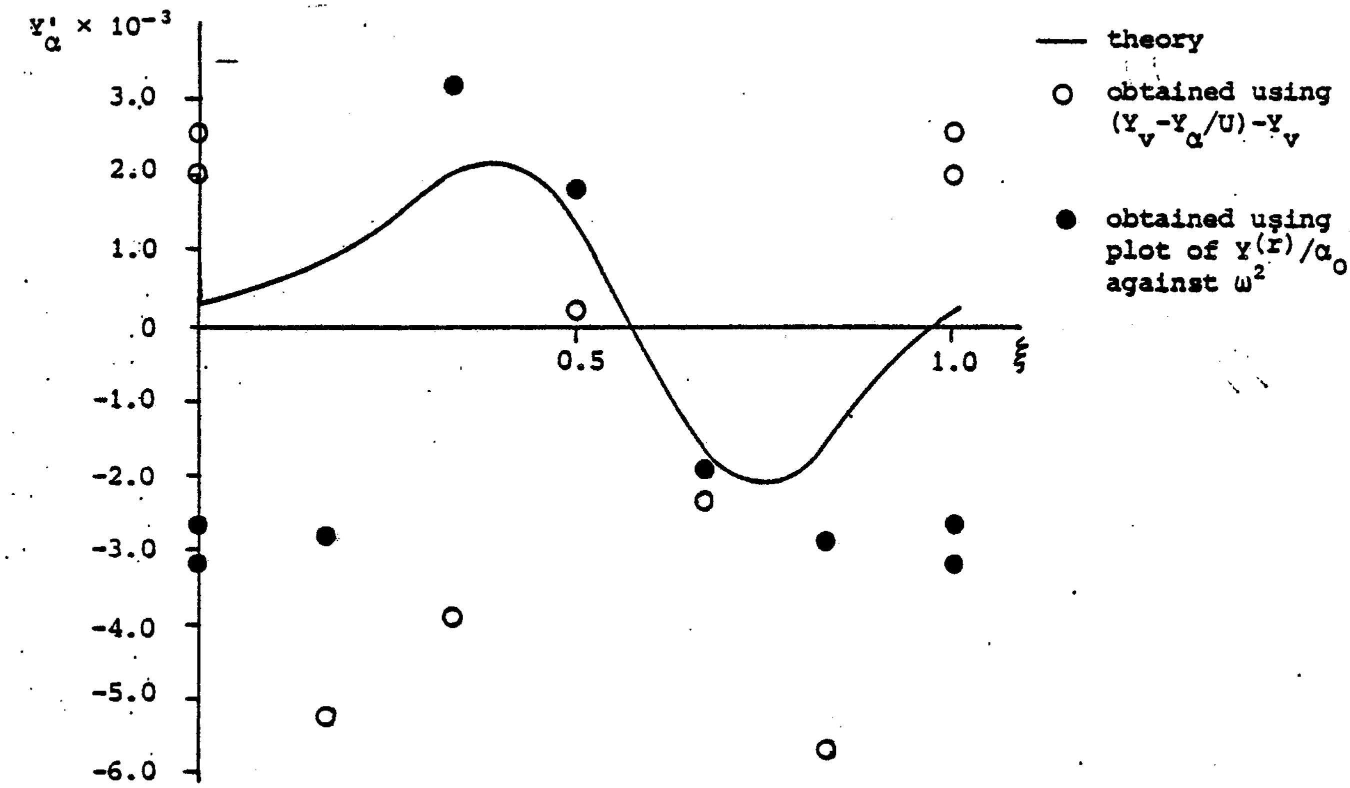

Figure 17. Y'_α as a function of ξ

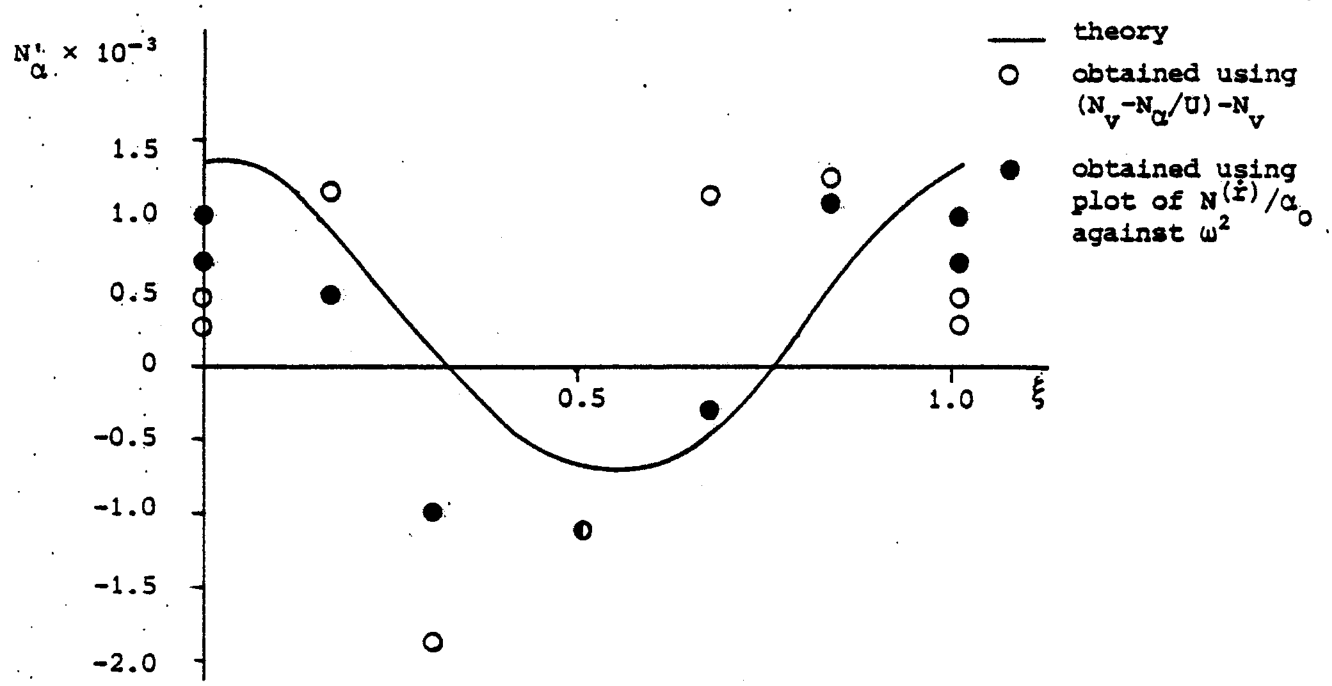

Figure 18. N'_α as a function of ξ

below the top of the rudder. Due to the many variables involved (including wake and propeller race effects) it is not possible to calculate the rudder derivatives directly. The calm water value is obtained from experiments and multiplied by the ratio of the calculated value in the wave to the calculated value in calm water. i.e.

$$Y_{\delta_{WAVE}} = Y_{\delta_{CALM}} \times \left(\frac{Y_{\delta_{WAVE}}}{Y_{\delta_{CALM}}} \right)_{CALCULATED}$$

The values obtained theoretically are compared with those found experimentally in figs. 5-18. Although agreement in some of the cases is poor the more important values seem to be agreeing reasonably well. Thus, it was possible to go onto the next stage which involved carrying out a simulation based on the model already developed and using the theoretical techniques outlined above to provide the values of the coefficients at each position in the wave.

SIMULATION

As the purpose of the simulation was not to predict highly accurate path records (the limitations of the model and the calculation of the coefficients prevented this) but to indicate under which conditions a broach would occur and to permit a closer study of why it occurred, it was decided to go for an analogue simulation method. This had the advantage of being quicker to run so that once it was set up more test cases could be investigated in a given period of time than with the digital simulation technique.

Thus, equations 3 - 10 were patched up on an EAI 2000 analogue computer as shown in figure 19. Because many of the coefficients varied with ξ it was necessary to use a digital computer to control their value. The way the system worked was that the simulation was started with the coefficients all set to the correct values. A counter was started which counted down to zero in approximately 0.05 of a second and then put the analogue computer into the HOLD mode. The value of ξ was sampled by the digital computer which reset the coefficients to the appropriate values and then put the analogue computer back into the OPERATE mode. This procedure was repeated until either the ship broached, three successive waves overtook it or the time limit elapsed. A typical result is given in figure 20.

The simulation was then repeated for a range of ship speeds and wave lengths with constant steepness and the broaching zone drawn

Figure 19.

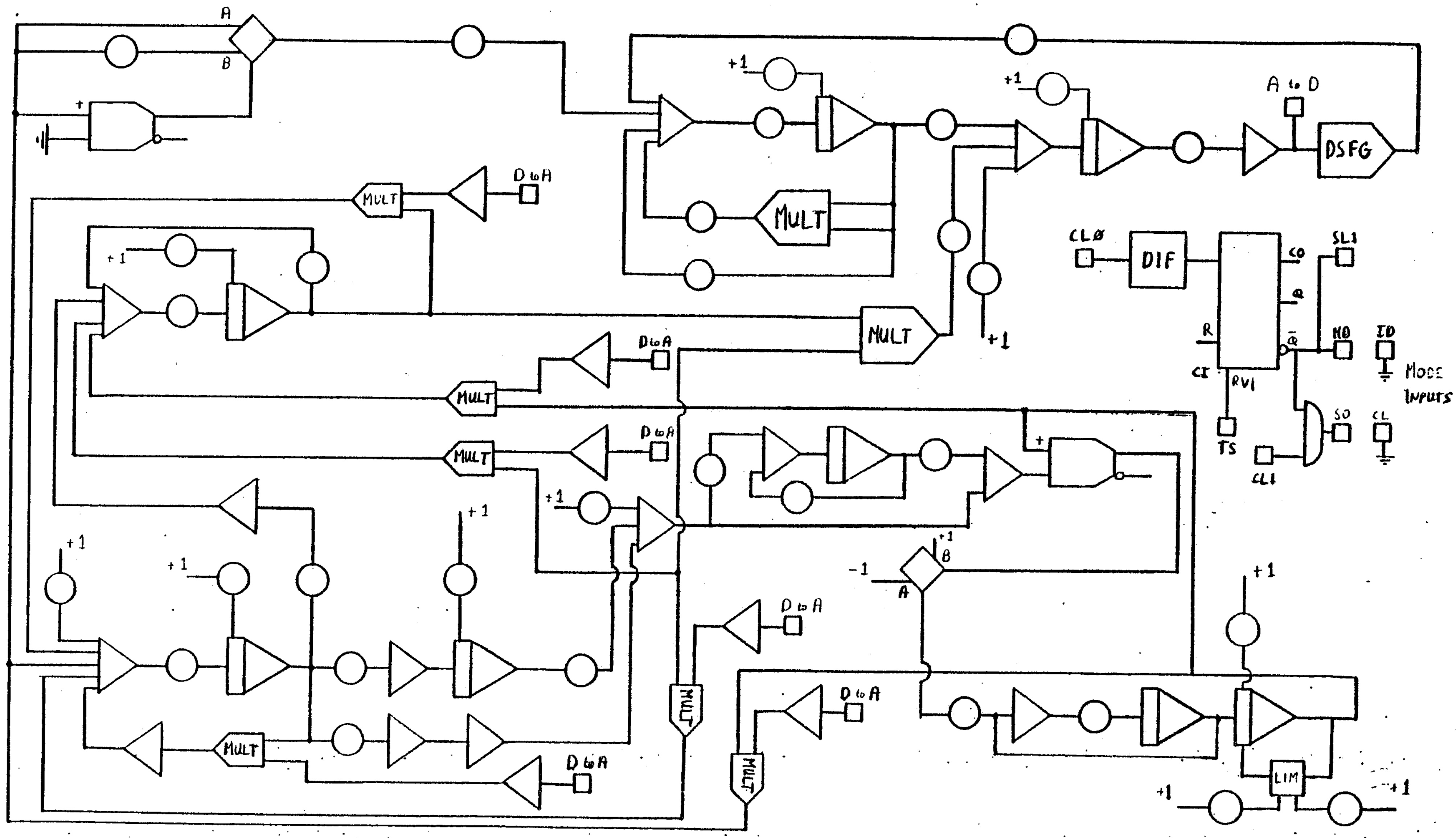

Figure 19. Patch diagram for complete hybrid simulation.

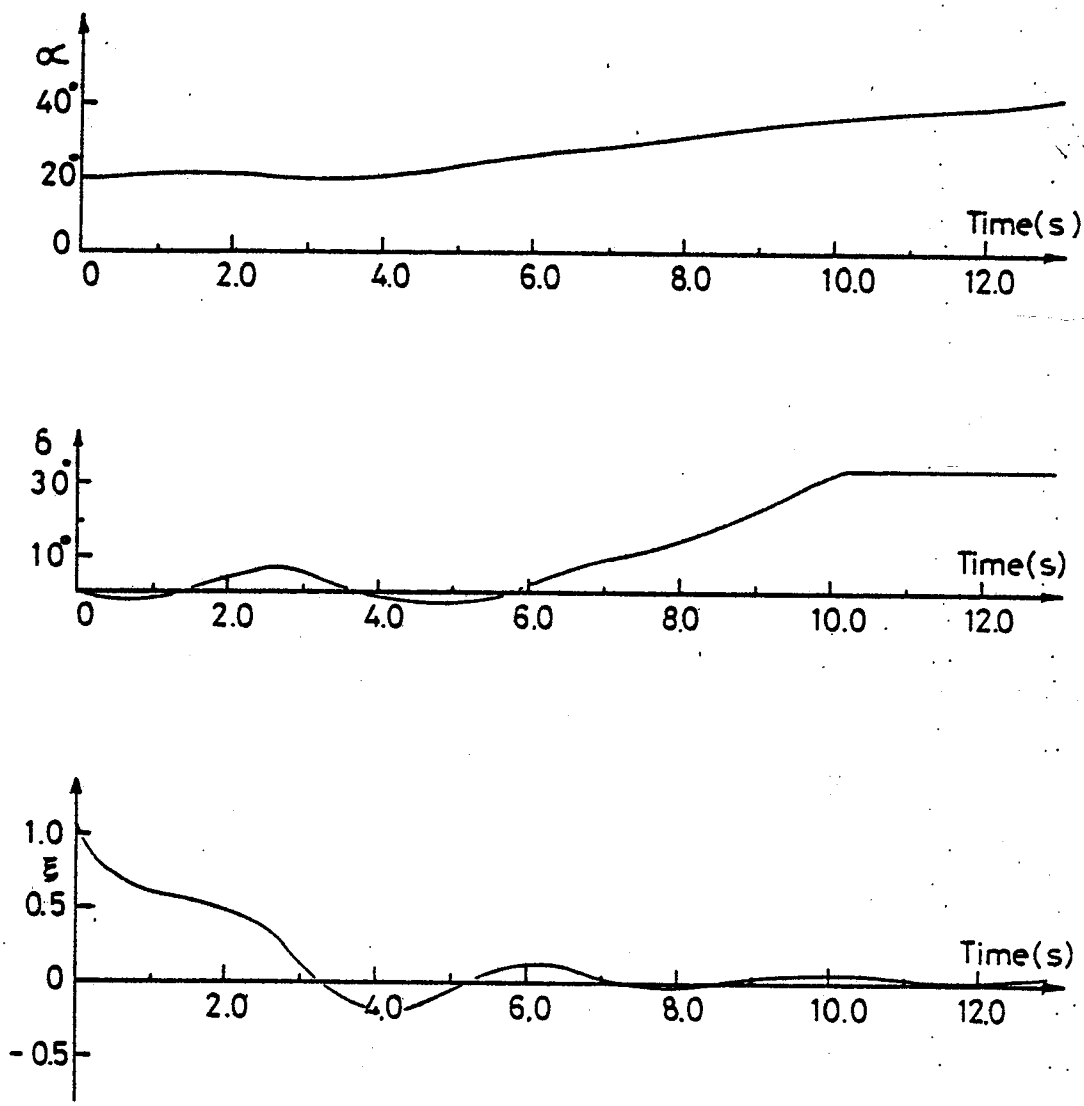

Figure 20. Record from simulation for: $\lambda/L = 0.9$, $F_{no} = 0.33$
½ depth rudder, $C_3 = 3°/\text{sec}$. full-scale,
time delay = 3 secs model scale

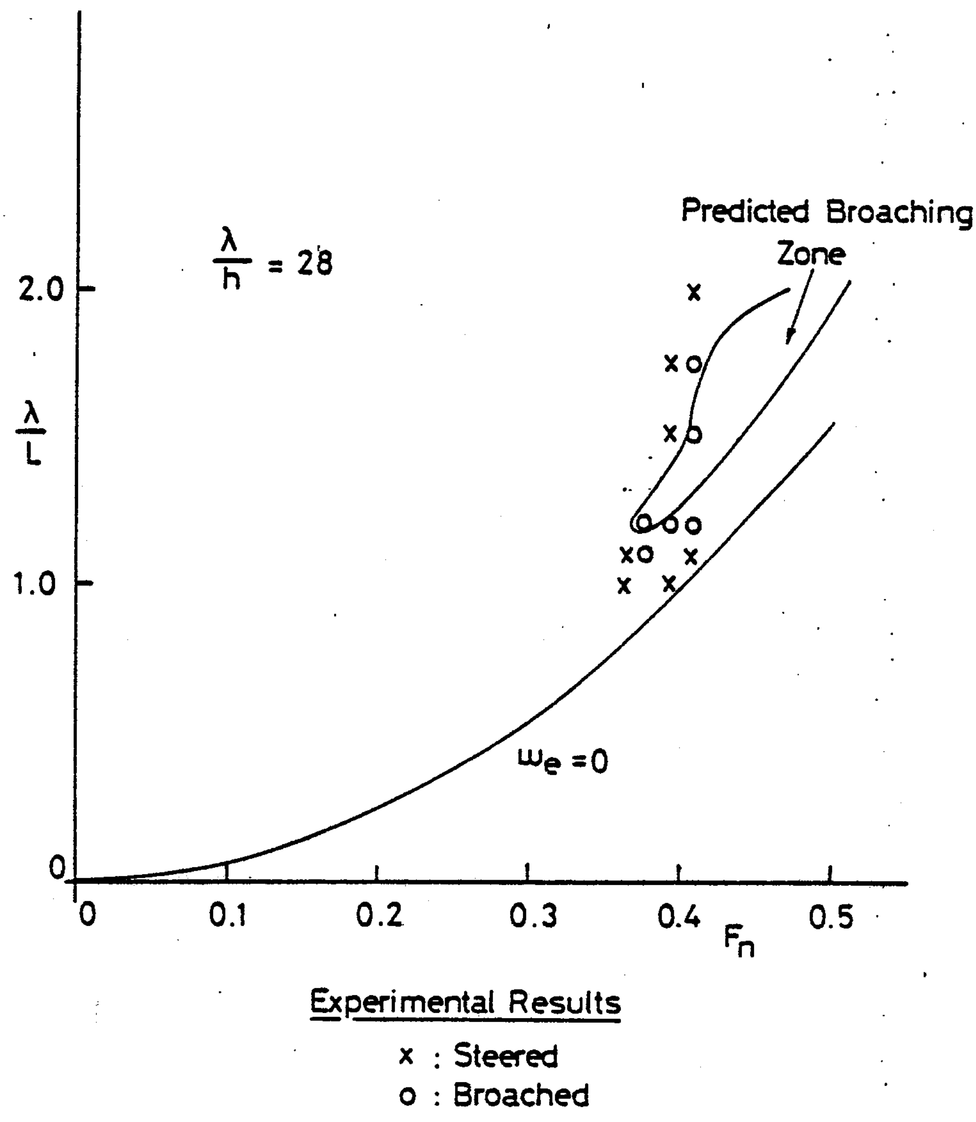

Figure 21 Comparison between predicted and experimental results for standard rudder

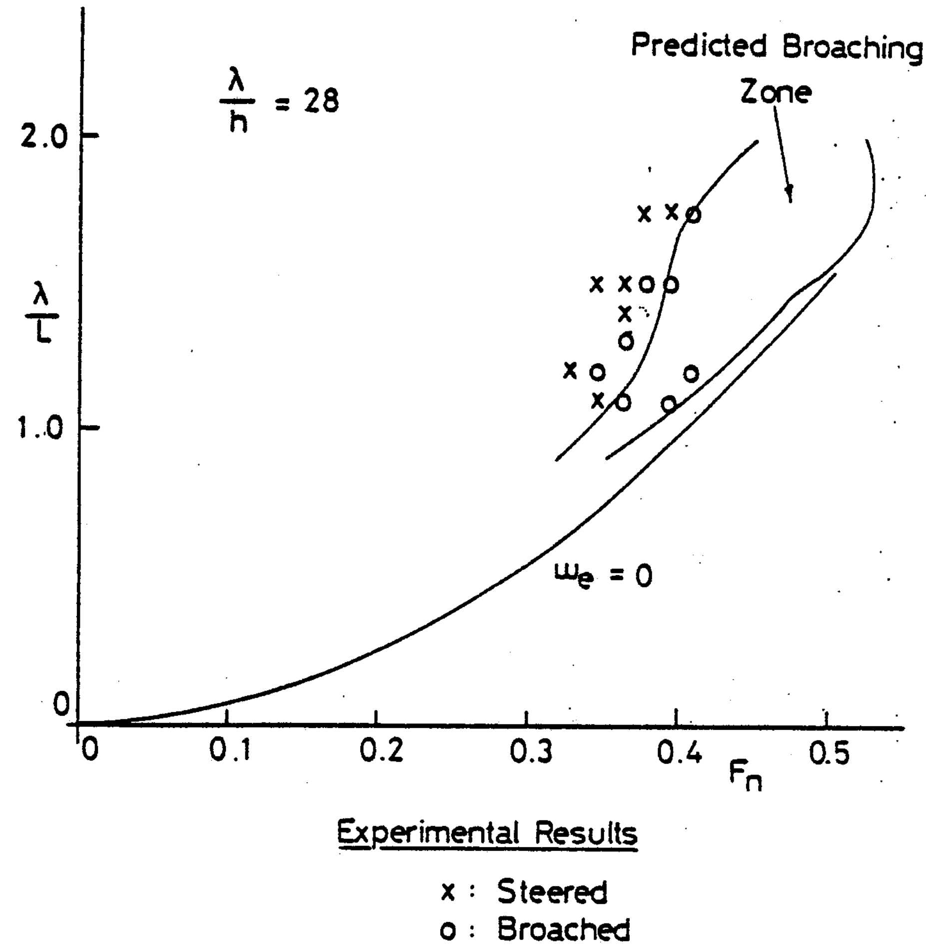

Figure 22 Comparison between predicted and experimental results for ½ depth rudder

on a plot of non dimensional wavelength against froude number. The results from the simulation are compared with those obtained for the same fine form model by Lloyd at AMTE (9) using free running model experiments. (Figures 21 & 22). Two rudder sizes were tested and it can be seen that when using the smaller rudder there is a much larger broaching zone.

The results from the simulation agreed reasonably well with those from the free running model experiments and so it was concluded that it must be representing the important factors in the broach reasonably well.

DISCUSSION

Since the simulation was shown to represent the broaching phenomena reasonably well it was possible to look closely at the results to see what caused the broach.

Essentially, there is a region of ξ when N_α is large and positive indicating a large wave induced yawing movement. This overlaps both the area of largest longitudinal wave force and the area of reduced rudder effectiveness making it a potentially dangerous position for the ship to be in. As the waves gradually overtake the ship it is forced to surge to near wave speed, thus it tends to spend a longish time in this dangerous position. It is the length of time it spends in this position, as well as the relative sizes of the wave induced yawing moment and the loss of rudder effectiveness that determines whether the ship will broach or not. In regular waves a ship travelling fast enough will be accelerated to wave speed and will settle at its longitudinal equilibrium position on the wave after passing reasonably quickly through the dangerous region. If the same ship was travelling slight slower it would spend a longer time in the dangerous region and hence would probably broach. If it were travelling slower still, the surging would not be so pronounced and the waves would overtake it before it had spent long enough in the dangerous region to broach.

The size of the dangerous region, and the magnitude of the danger will, for a given ship depend on the wavelength, steepness, rudder size and heading angle. The effect of varying steepness and heading angle on the broaching zone can be seen in figures 23 and 24.

CONCLUSIONS

The conditions under which a broach will occur in regular waves can be determined by using the simulation technique outlined in the paper, which is based on the linear manoeuvring equations with coefficients varying as functions of the ships longitudinal position in the wave.

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The principle cause of the broach is the large wave induced yawing moment which occurs at around the same longitudinal position as the loss in rudder effectiveness resulting in an unbalanced moment causing to the ship to yaw.

Whether a ship will broach or not depends on how long it spends in this region (which in turn depends on its initial speed), and on how large the unbalanced moment is, (which for a given ship depends on wave length, steepness, rudder size and heading angle).

ACKNOWLEDGEMENTS

The work described in the paper was carried out at the University of Glasgow, the National Maritime Institute and the Admiralty Marine Technology Establishment and the author would like to thank all those concerned.

NOTATION

C_3	Maximum rudder rate
Fn	Froude number
GM	Transverse metacentric height
h	Wave height
I_z	Moment of inertia about the z-axis
L	Ship length
m	Ship mass
N_r	Yaw moment derivative with respect to angular velocit
$N_{\dot{r}}$	Yaw moment derivative with respect to angular acceler
N_v	Yaw moment derivative with respect to sway velocity
$N_{\dot{v}}$	Yaw moment derivative with respect to sway accelerati
N_α	Yaw moment derivative with respect to heading angle
N_δ	Yaw moment derivative with respect to rudder angle
N_ϕ	Yaw moment derivative with respect to roll angle
P_1	Autopilot proportional control constant
P_2	Autopilot rate control constant
r	Angular velocity
$\dot{r}$	Angular acceleration
t	time
U	Ship speed
u	Surge velocity
$\dot{u}$	Surge acceleration
v	Sway velocity
$\dot{v}$	Sway acceleration
X	Component of force along x-axis
X_r	Surge force derivative with respect to angular veloci
X_u	Surge force derivative with respect to surge velocity

$X_{\dot{u}}$	Surge force derivative with respect to surge acceleratio
X_v	Surge force derivative with respect to sway velocity
X_δ	Surge force derivative with respect to rudder angle
X_ξ	Wave induced surge force
X_{PROP}	Thrust from the propeller
x_G	x co-ordinate of the centre of gravity
Y	Component of force along y-axis
Y_r	Sway force derivative with respect to angular velocity
$Y_{\dot{r}}$	Sway force derivative with respect to angular acceleratio
Y_v	Sway force derivative with respect to sway velocity
$Y_{\dot{v}}$	Sway force derivative with respect to sway acceleration
Y_α	Sway force derivative with respect to heading angle
Y_δ	Sway force derivative with respect to rudder angle
Y_ϕ	Sway force derivative with respect to roll angle
α	Heading angle
α_d	Desired heading angle
δ	Rudder angle
δ_a	Actual rudder angle
δ_{a_m}	Maximum rudder angle
$\dot{\delta}_a$	Actual rudder rate
δ_d	Desired rudder angle
λ	Wavelength
ξ	Non-dimensional x* co-ordinate of the stern (i.e.distance from crest to transom,measured positive where transom is ahead of crest, divided by wavelength.)
ρ	Mass density of water
ϕ	Roll Angle
ψ	Heading error (= $\alpha - \alpha_d$)
$\dot{\psi}$	Heading error rate

Superscript ' indicates that the quantity has been non-dimensionalised as follows:

Non-dimensional mass $= m' = m/\frac{1}{2}\rho L^3$

Non-dimensional force $= x' = x/\frac{1}{2}\rho L^2 U^2$

Non-dimensional velocity component $= v' = v/U$

Non-dimensional angular velocity component $= r' = r\,L/U$

Non-dimensional acceleration component $= \dot{v}' = \dot{v}\,L/U^2$

Non-dimensional angular acceleration component $= \dot{r}' = \dot{r}\,L^2/U^2$

Etc.

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