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Computer Simulations for Prediction of Manoeuvring Properties

by
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SUMMARY

Predictions of manoeuvring properties are most commonly made by use of different model test techniques. Free-running tests with a self propelled model or captive model tests combined with computer simulations are often carried out. However, model tests sometimes prove to be relatively costly, why they are normally carried out only at one stage during the design of the ship and then quite often at a relatively late phase. Since in fact ships to a great extent are designed on previous experience, this does not normally give rise to any problems. However, every now and then the importance of the manoeuvring aspect seems to be somewhat underestimated, and serious problems may appear during delivery trials or later on.

In order to minimize problems of these kinds SSPA has developed a computer simulation program called NAVMAN (NAVal ship MANoeuvring), which will enable designers to predict the manoeuvring properties of a new design at a relatively early stage and at a comparatively low cost.

1. INTRODUCTION

The manoeuvring properties of a new ship design can be predicted by use of one of three main methods:

1) Semi-empirical calculations based on statistical data from model tests, full scale trials and possibly computer simulations.

2) Free-running model tests

3) A combination of captive model tests and computer simulations.

Often, in an early design phase, the first alternative is chosen. The manoeuvring characteristics are then determined either by comparing statistical data or by theoretically calculating hydrodynamic coefficients. In the latter case tha coefficients are entered into a mathematical model and computer simulations are performed. In the two last alternatives a model test basin is required.

Using the free-running tests, the model is equipped with motors, propellers and rudder servos. It is controlled by an autopilot to follow a preset heading. At SSPA the tests are carried out in the Maritime Dynamics Laboratory (MDL), which is a basin 88 by 39 m, spanned by a large multimotion carriage. An x-y positioner connecting the model to the carriage gives the control signals to the carriage without transferring any forces to the model. The carriage is therefore in this control mode chasing the model.

A number of standard manoeuvres such as turning circles and zig-zag tests are carried out at different speeds and rudder angles. Often, also roll decay tests at different speeds are carried out with the free-running model in order to define roll radius of gyration in water and the roll damping ability.

The set-up for the captive tests is nearly the same as for the free-running tests, the difference being that the model is now connected to a balance keeping it restrained in surge, sway roll and yaw and measuring the forces and moments in these directions, while it is still free to heave and trim. The results from the tests are then, in the form of hydro-dynamic coefficients entered into a computer simulation program, and the following simulations will provide the manoeuvring characteristics.

Based on experience from all these three methods a computer simulation program has been developed. The philosophy when designing the program was to make the use of it as simple as possible, making it easy for the designer, already at an early stage, to predict the manoeuvring properties.

The paper briefly presents the structure of the program. In order to show what can be gained by using the program a systematic series of simulations of a 125 m frigate has been performed. The effect of different rudder arrangements, vertical centre of gravities have been visualized by the execution of a series of simulated standard manoeuvres.

2. STATISTICAL DATA FROM MODEL TESTS

The development of the computer program was possible thanks to an extensive set of model test data. The tests were all carried out in SSPA Maritime Dynamics Laboratory, mostly with free sailing models of naval vessels. The scale factor varied between 8 and 30 and the material comprises turning circles, zig-zag manoeuvres and roll decay tests at different speeds and rudder angles and as for the zig-zag manoeuvres for different heading deviations. Tests have been carried out for ships with lengths between 20 and 150 m and with displacements between 35 and 6200 tonnes.

Contrary to what is experienced from conventional merchant ships the speed has for semi-displacement vessels a great influence on the manoeuvring characteristics. This is visualized by Fig. 1 where the tactical diameters for most of the turning tests carried out at SSPA are given on basis of Froude number. It is given in a non-dimensional way, divided by the ship length. Furthermore it is corrected for rudder angle, rudder area and aspect ratio of rudder, since all these parameters significantly affect the turning diameter. For dynamically course stable ships the product $TD \cdot \delta$ is, for rudder angles below stalling, more or less constant for one and the same ship. The rudder force can within reasonable limits be assumed to be proportional to the product of relative rudder area and the aspect ratio of the rudder.

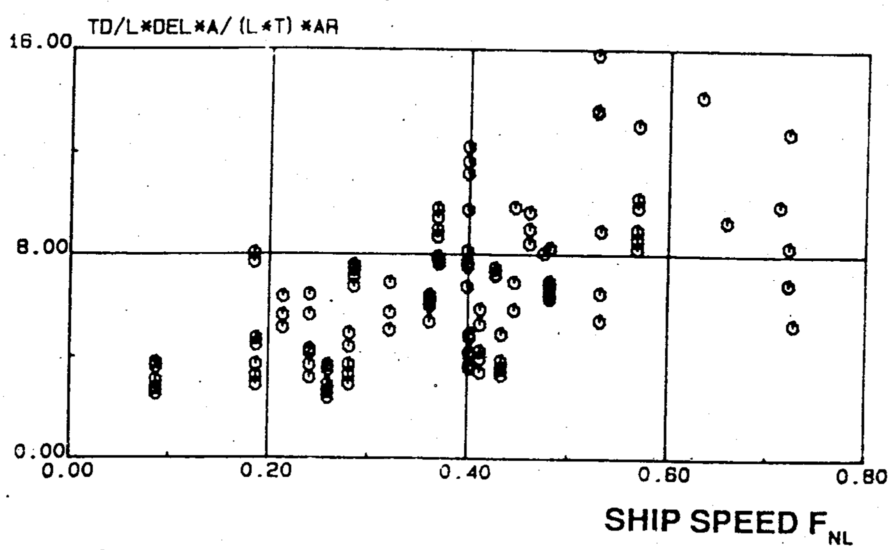

Fig. 1. Speed dependence on turning circles

As is apparent from the diagram the influence from the speed is not unambiguous. The scatter is extensive. The form of the hull, such as relations between the main particulars length, beam, draught, displacement etc and section forms are of course of great importance.

The zig-zag manoeuvres do not directly show such an influence of the speed, see Figs 2-3. However, all the ships tested are clearly stable on course with relatively small overshoot angles. A higher speed will, at the same time as it makes the ship more stable, also make the rudder respond comparatively more slowly. After having ordered counter rudder the ship will continue its turning rate until the midship rudder is passed. As the turning rate is more or less proportional to the speed, a higher speed will for the same absolute time entail a larger heading deviation.

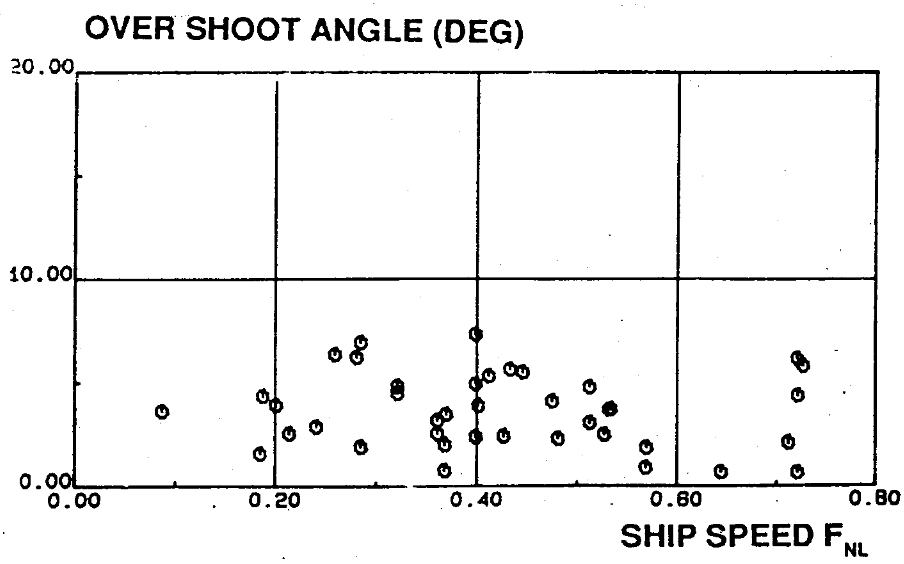

Fig. 2. Speed dependence on Z 10/10

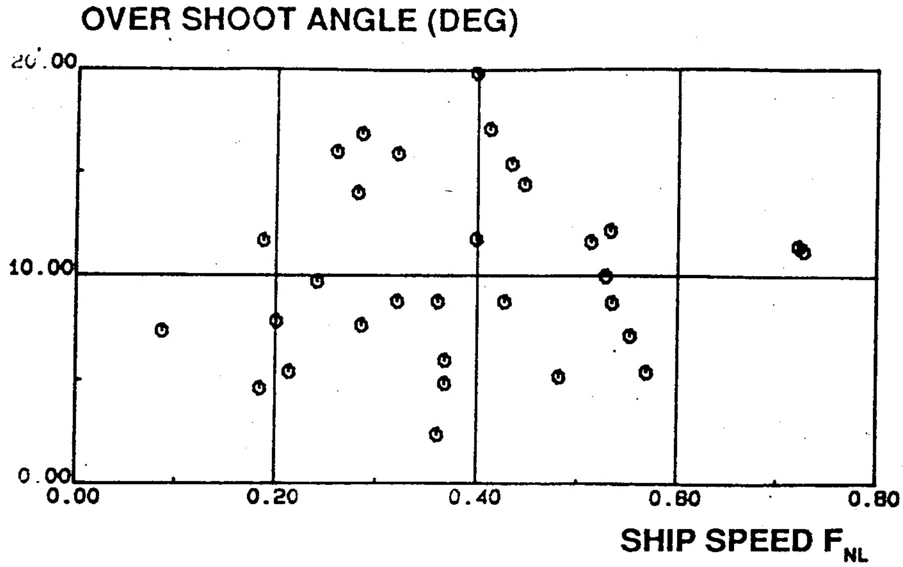

Fig. 3. Speed dependence on Z 20/20.

3. PROGRAM "NAVMAN"

The computer program NAVMAN is used for time domain computer simulations of the motions of an arbitrary ship. In the program the motions are represented by a mathematical model based on the rigid body dynamics, and on hydrodynamic forces and moments.

3.1 Mathematical model

The model covers four degrees of freedom. Surge, sway, roll and yaw. The hydrodynamic forces and moments are represented by polynomials comprising all the hydrodynamic forces that may be significant in describing the ship motion.

The variables used to describe the motions are explained in Fig 4. The projections of the total ship speed V on the x- and y-axes are the surge velocity u and the sway velocity v. The yaw rate is denoted r and the heading and rudder angles are denoted ψ and δ. The roll motion is characterized by the roll angle φ and the roll rate p.

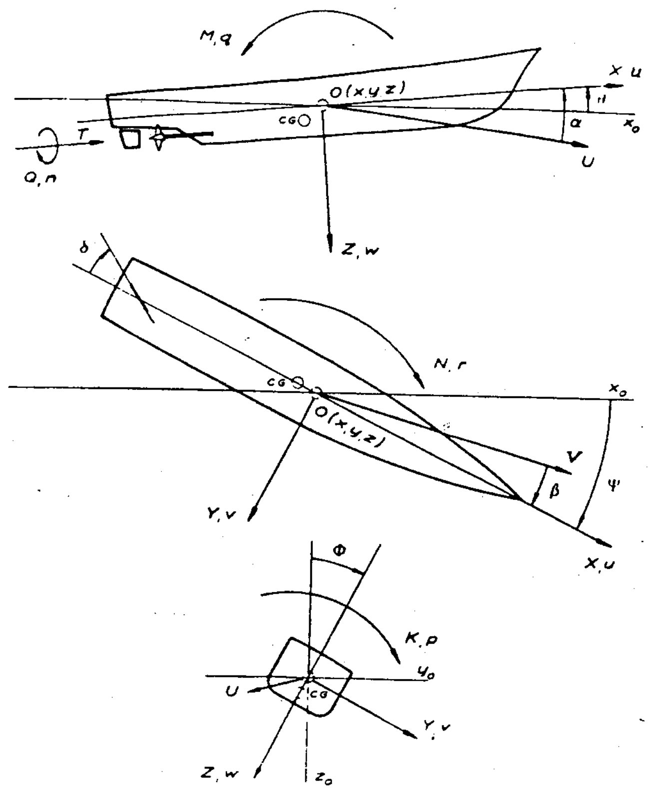

Fig. 4 Coordinate system

The principal design of the mathematical model is given by

$$(m - x_{\dot{u}})\dot{u} = x_{tot}$$

$$\begin{bmatrix} (m-Y_{\dot{u}}) & -(mz_G + Y_{\dot{p}}) & mx_G - Y_{\dot{r}} \\ -(mz_G + K_{\dot{u}}) & mk_{xx}^2 - K_{\dot{p}} & -(mx_G Z_G + K_{\dot{r}}) \\ mx_G - N_{\dot{u}}) & -(mx_G Z_G + N_{\dot{p}}) & mk_{zz}^2 - N_{\dot{r}} \end{bmatrix} \begin{bmatrix} \dot{v} \\ \dot{p} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} Y_{tot} \\ K_{tot} \\ N_{tot} \end{bmatrix} \quad (1)$$

where the index "tot" denotes the total forces on the hull, that is in this case hydrodynamic and wind forces and moments.

a) Hydrodynamic forces

The hydrodynamic forces comprise linear as well as non-linear forces. The basic structure of the manoeuvring model has been described in detail elsewhere [1,2,3,4,8] and will only be commented upon here.

The functions that approximates the forces and moments are formally expressed by Taylor expansion around the state of equilibrium with respect to the quantities affecting the different motions. The polynomial coefficients thus describing the hydrodynamic forces and moments are calculated on basis of various theories [1, 4] and model tests.

The relations between speed, number of propeller revolutions and propeller thrust are expressed as second order functions K_T and K_Q on basis of the advance number J according to

$$K_T = K_{TO} + K_{TJ} \cdot J + K_{TJJ} \cdot J^2$$
$$K_Q = K_{QO} + K_{QJ} \cdot J + K_{QJJ} \cdot J^2$$

where

$$J = \frac{u(1-w)}{n \cdot D}$$

is the advance number.

b) Wind forces

Many problems have been experienced for ships with high superstructures due to wind influence. The program includes a calculation of the wind forces according to Isherwood [5]. The calculation is based on the size and the distribution of the wind areas of the ship, i.e. the lateral and transverse projected area, respectively, above the waterline. The wind fluctuations around the average wind speed, experienced in real life, are in the mathematical model taken care of by a power spectrum of wind turbulence, see Davenport [6].

Once all the necessary data of the ship have been entered, the program calculates the so called hydrodynamic coefficients automatically. The calculation is based on theories and on the previous described model tests.

3.1 Input data

The necessary data to be entered are specified in Appendix A and will be somewhat commented upon here.

a) Hull data

As the actual displacement to be tested might not be the same as the full load displacement, the latter is also specified. The static stability on the craft is defined by either the metacentric height GM or by an arbitrary number of righting arm values related to equal number of roll angles. In the former case the righting arm is achieved from

$GZ = GM \sin\varphi$

and consequently the restoring moment

$K(GZ) = -mg\, GM \sin\varphi$

b. Propeller data

An arbitrary number of propellers can be entered. If the propeller is not yet defined, the program will automatically design it, based on the decided propeller rate and speed at max continuous rating.

3.2 Calculation of hydrodynamic coefficients

The coefficient calculation procedure is outlined in the block diagram below.

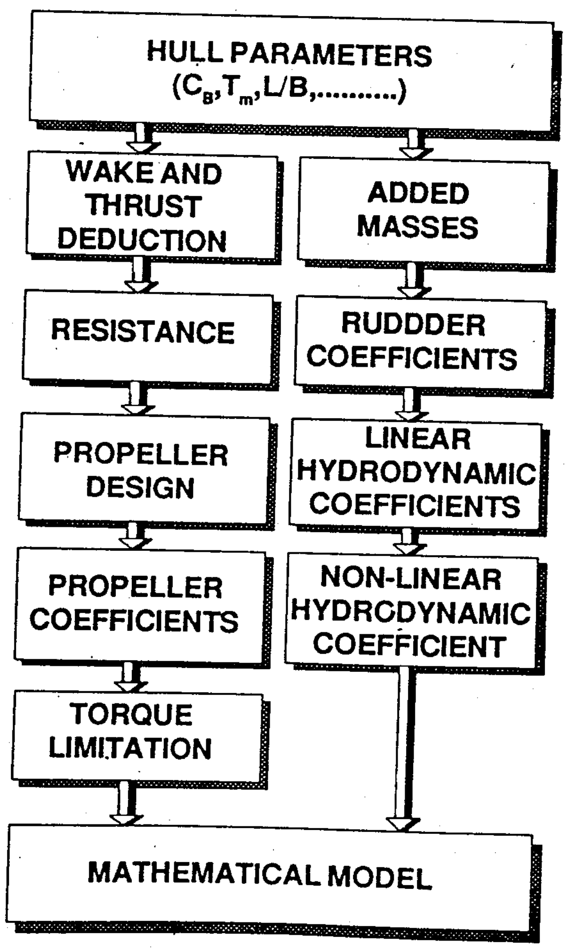

Fig. 5. Coefficient calculation procedure

a) Propeller design

The calculation of wake and thrust deduction facor is calculated based on speed, block coefficient, displacement and propeller shaft angle, see Ref [7].

Not being essential for the manoevring properties the resistence is calculated in a relative simple way. The wetted surface is achieved from

$$S_W = 2.8 \, (\nabla \cdot L)^{1/2} + 2 \cdot A_r$$

and the total resistance at service speed

$$R = 0.5 \cdot \varphi \cdot S_W \cdot u_d^2 \cdot C_{RS}$$

where C_{RS} is the resistance coefficient.

The reliability of the program is visualized by Figs 6-7, showing tactical diameters and stationary speeds. The former compares predicted diameter with that measured in the model tests. For these to agree to 100 per cent all observations would have to form the diagonal straight line in the diagram. Fig 7 shows a corresponding comparison between stationary speeds in predicted and measured turning circles.

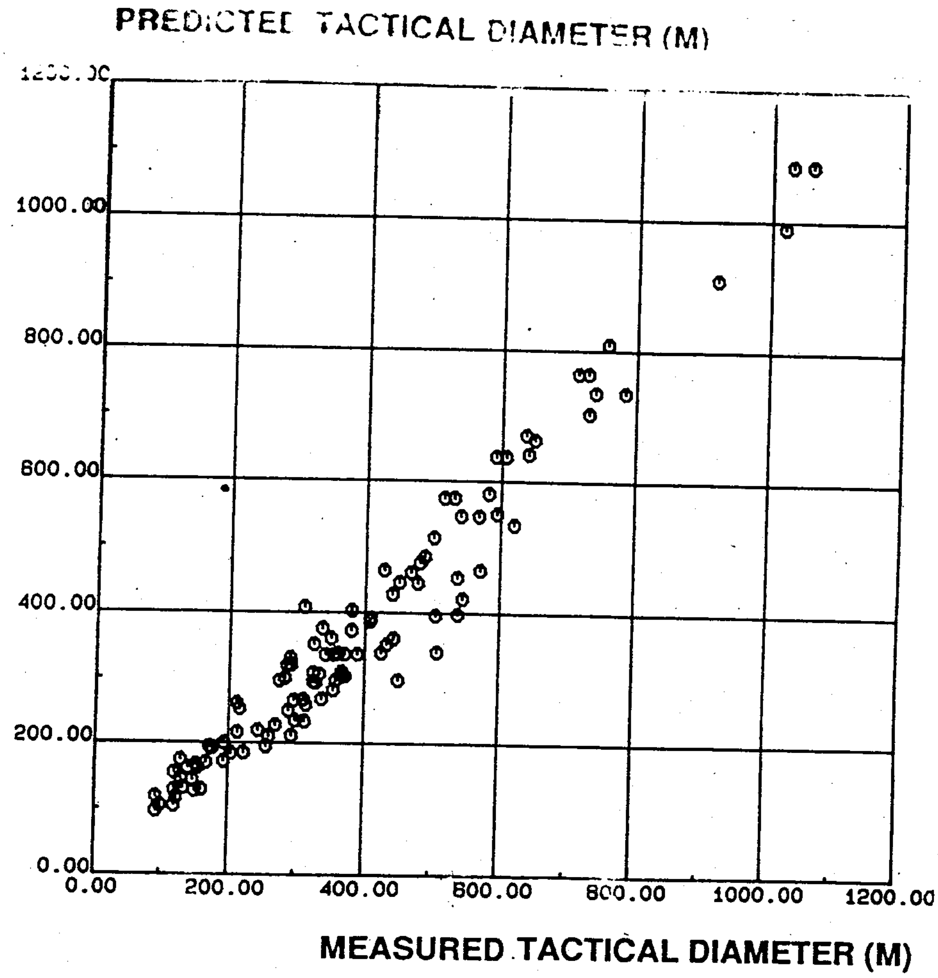

Fig. 6. Tactical diameter in turning circles

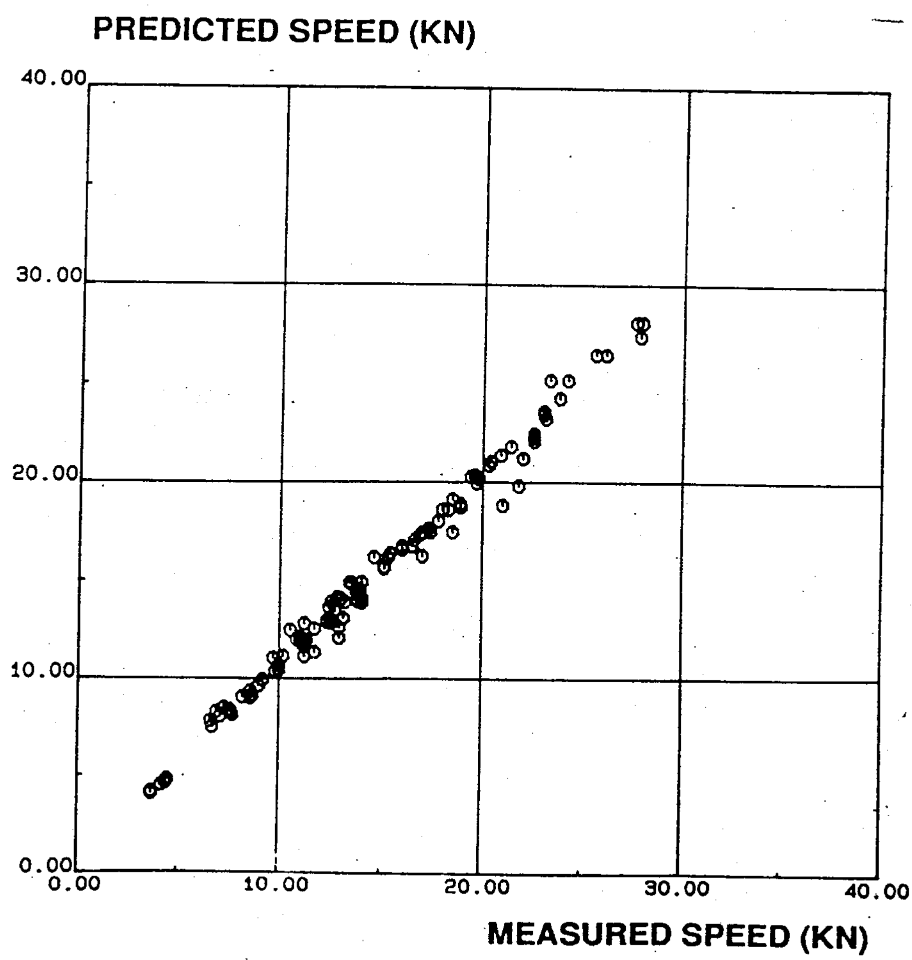

Fig. 7. Stationary speed in turning circles

4. SIMULATED STANDARD MANOEUVRES WITH PROTOTYPE SHIP

For the purpose of illustrating how the program can be used a study of a frigate is carried out.

4.1 Ship data

The chosen vessel is a 125 m long frigate with a displacement of 2 500 tonnes. All the data are summarized in Table 1.

Table 1

L = 125 m	T_9 = 4.08 m	A_r = 6.56 m²
B = 14.0 m	T_{10} = 0.0 m	A_{rh} = 0
B_{WL} = 13.2 m	∇ = 3500 m^3	h_r = 3.5 m
T_A = 4.2 m	∇_F = 3500 m^3	h_{pr} = 1.32 m
T_F = 4.2 m	A_{skeg} = 0	$\dot{\delta}$ = 4°/s
T_O = 1.15 m	x_G = -2.5 m	λ_N = -60.0 m
T_1 = 4.2 m	z_G = -1.625 m	λ_K = 2.5 m
T_2 = 4.2 m	k_{xx} = 4.75 m	n_p = 2
T_3 = 4.2 m	k_{zz} = 30.0 m	D = 2.64 m
T_4 = 4.2 m	BR = 2	P/D = 1.35
T_5 = 4.2 m	BK = 0	α_s = 11.0
T_6 = 4.2 m	GM = 1.4	H = 2.81 m
T_7 = 4.2 m	n_{GZ} = 0	n_d = 5 rps
T_8 = 4.2 m	n_{rud} = 2	u_d = 14.4 m/s

4.2 Predicted standard manoeuvres

A number of turning circles and zig zag manoeuvres were predicted for the frigate.

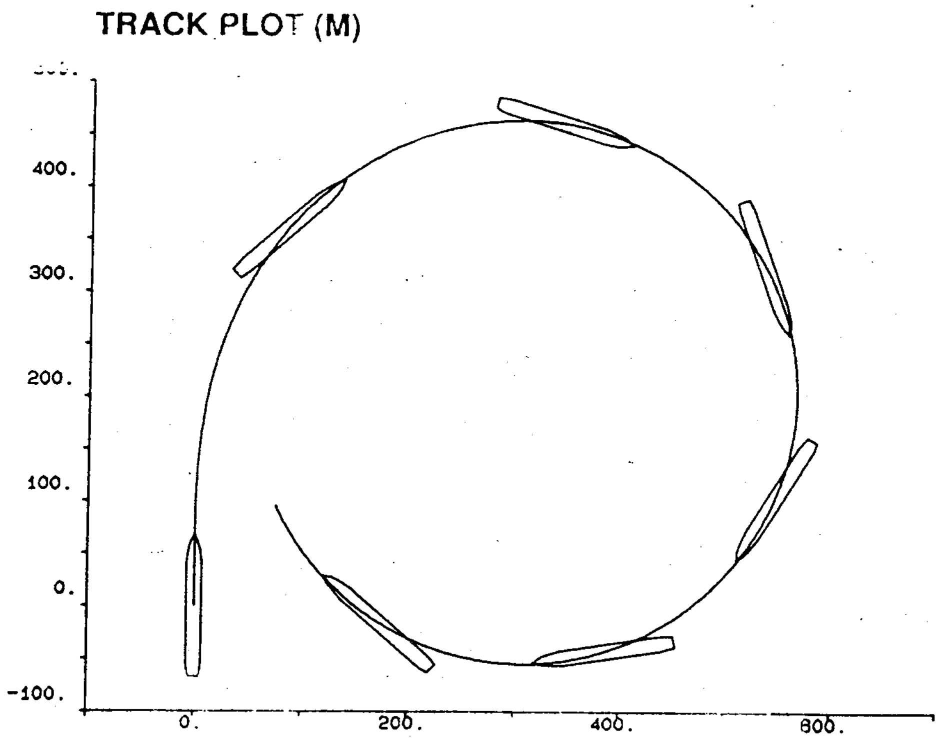

Fig. 8. Track plot for a 35 deg turning circle

Fig 8 shows the track plot for a 35-deg starboard turning circle at 28 knots' approach speed. The outline of the vessel is plotted once per thirty seconds. Due to an increased induced resistance, both on the hull and on the rudder and due to the axial component of the centrifugal force the speed drops significantly during the turn, as is shown in Fig 9.

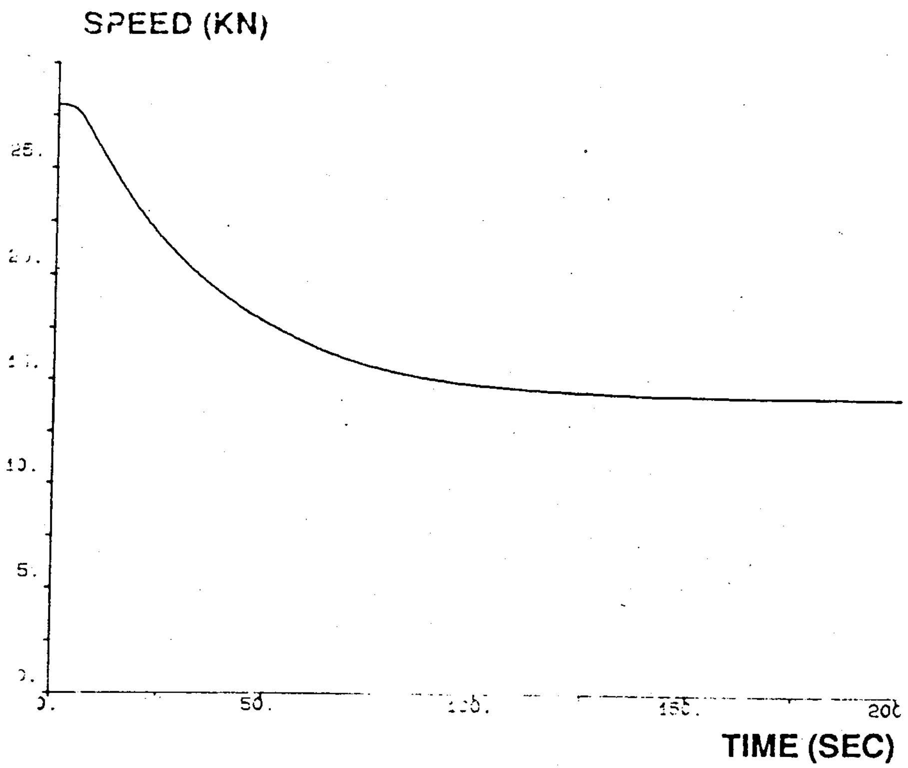

Fig. 9. Speed in a 35 deg turning circle

In the initial phase the craft heels to starboard due to the rudder force. After a while the centrifugal roll moment takes over and makes it roll outwards and as the speed drops this outward roll decreases somewhat, see Fig 10.

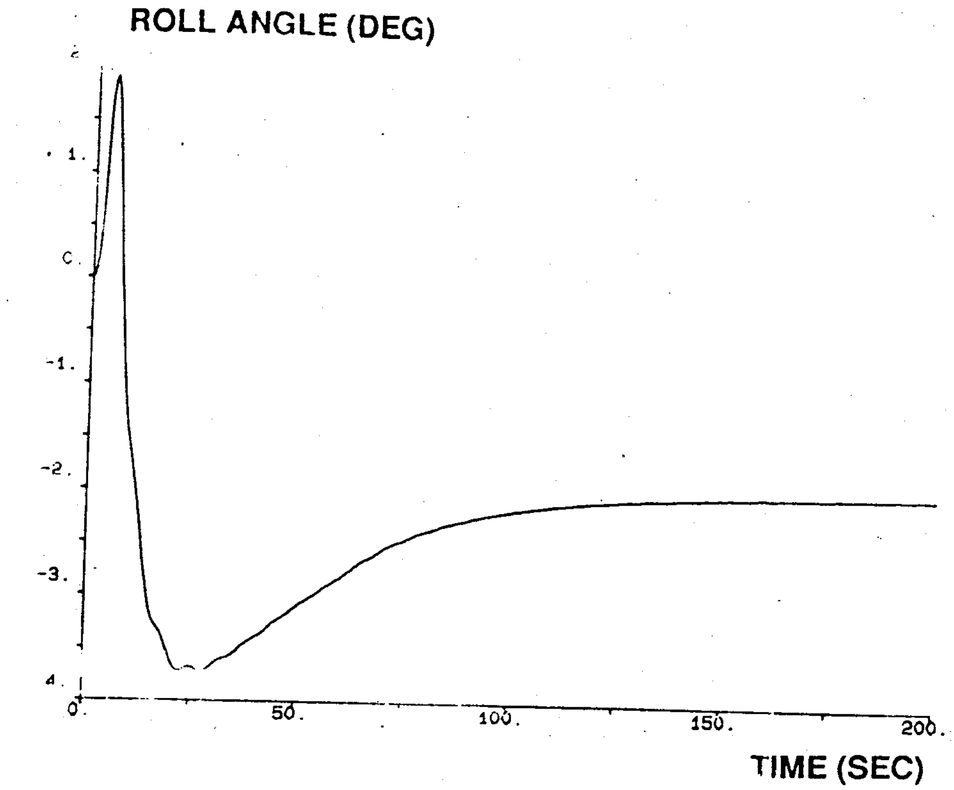

Fig. 10. Roll in a 35 deg turning circle

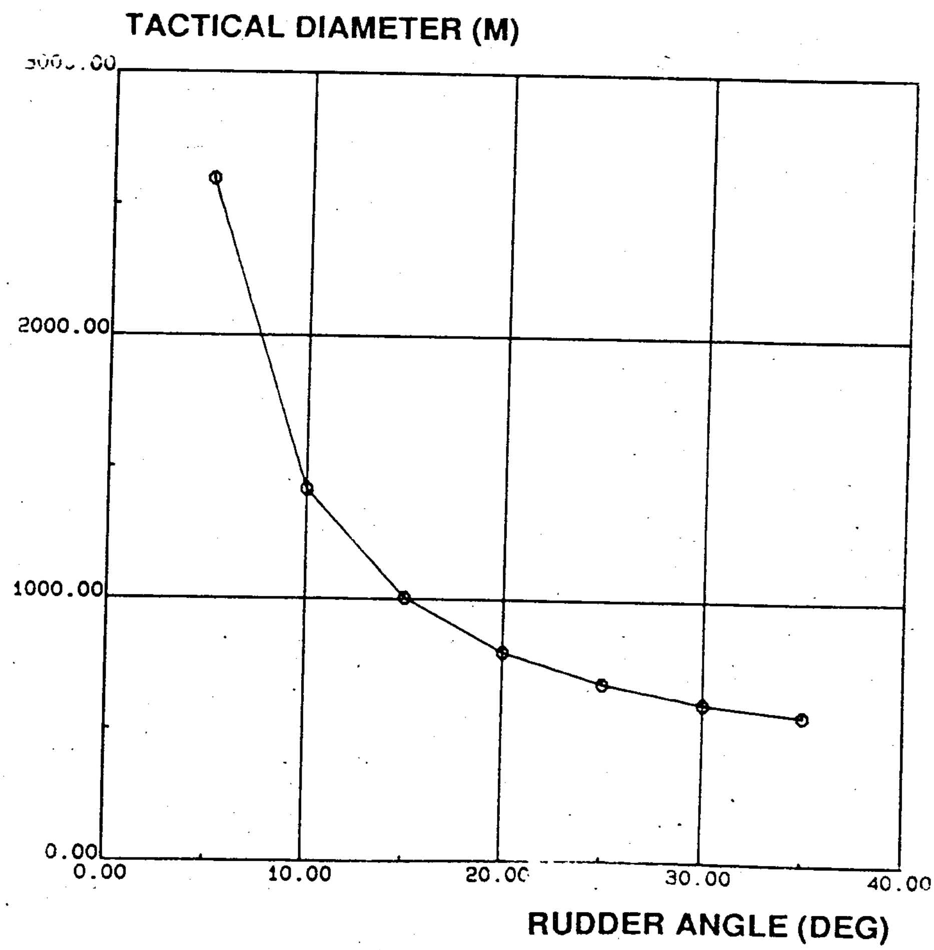

Fig. 11. Tactical diameter for different rudder angles

Fig 11 shows how the tactical diameter varies with the rudder angle. An angle of 5 degrees will provide a tactical diameter of approximately 2600 m, while a 35-degree rudder angle will give a tactical diameter of about 560 m

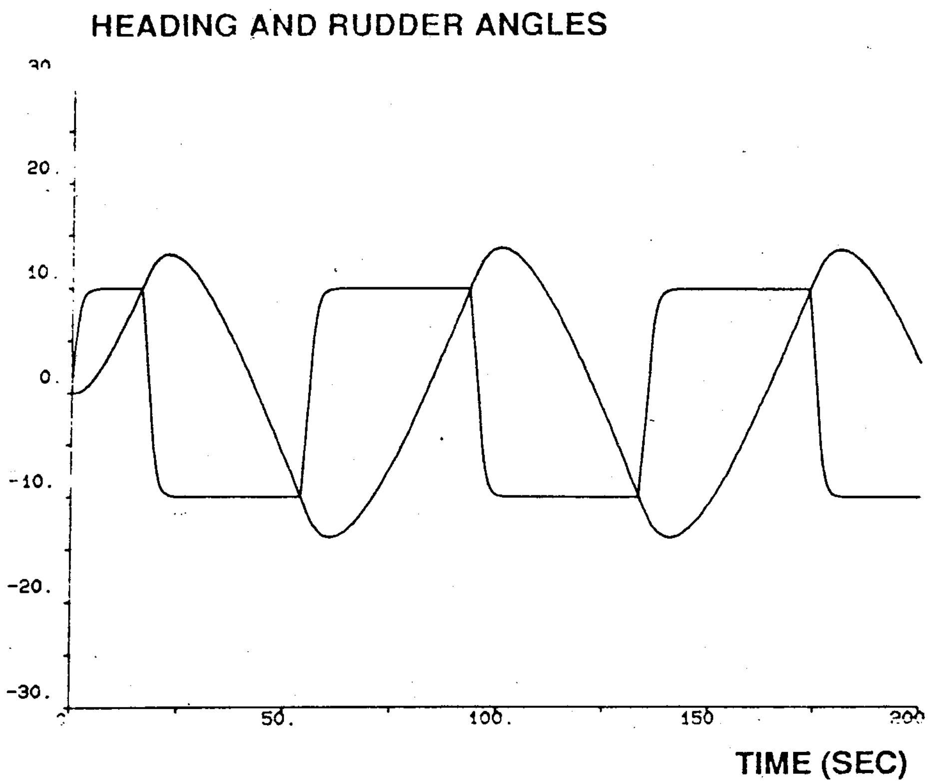

Fig. 12. Rudder and heading angles in a 10/10 deg zig-zag test

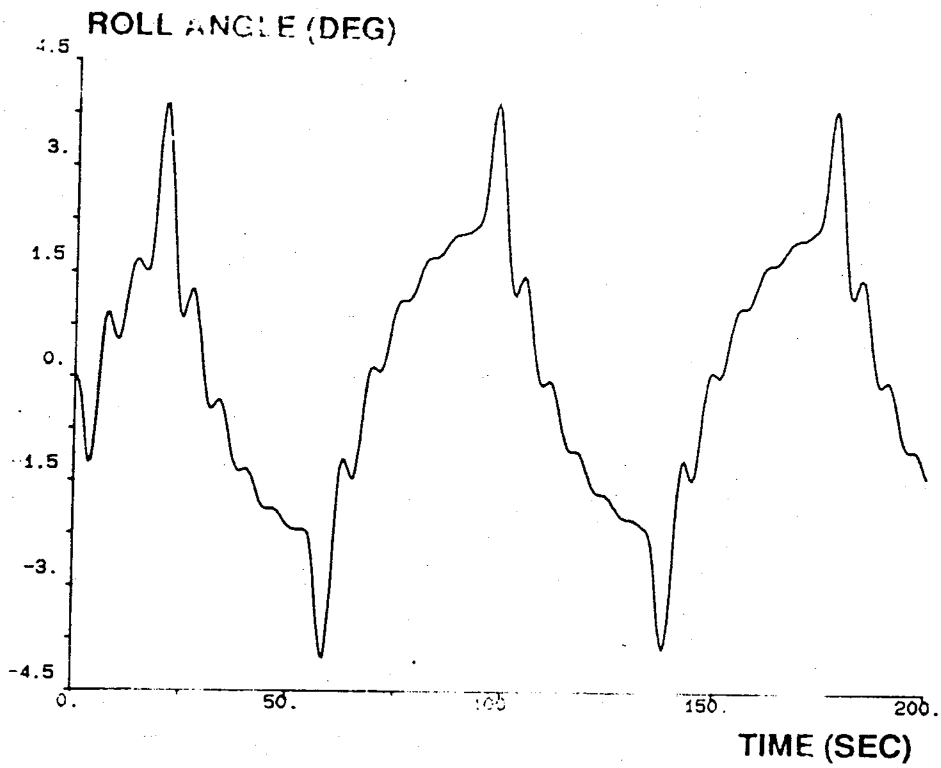

Fig. 13. Roll angle in a 10/10 deg zig-zag test

Figs 12-13 show results of a predicted 10/10 degree zig zag manoeuvre. As is illustrated the ship is rolling with amplitudes of about 4 degrees. Note the superimposed roll motion in the natural period.

The speed influence is in this case not so dominating as is shown in Fig 14. The Froude number does not exceed 0.41. The main effect is normally achieved for Froude numbers between 0.40 and 0.60.

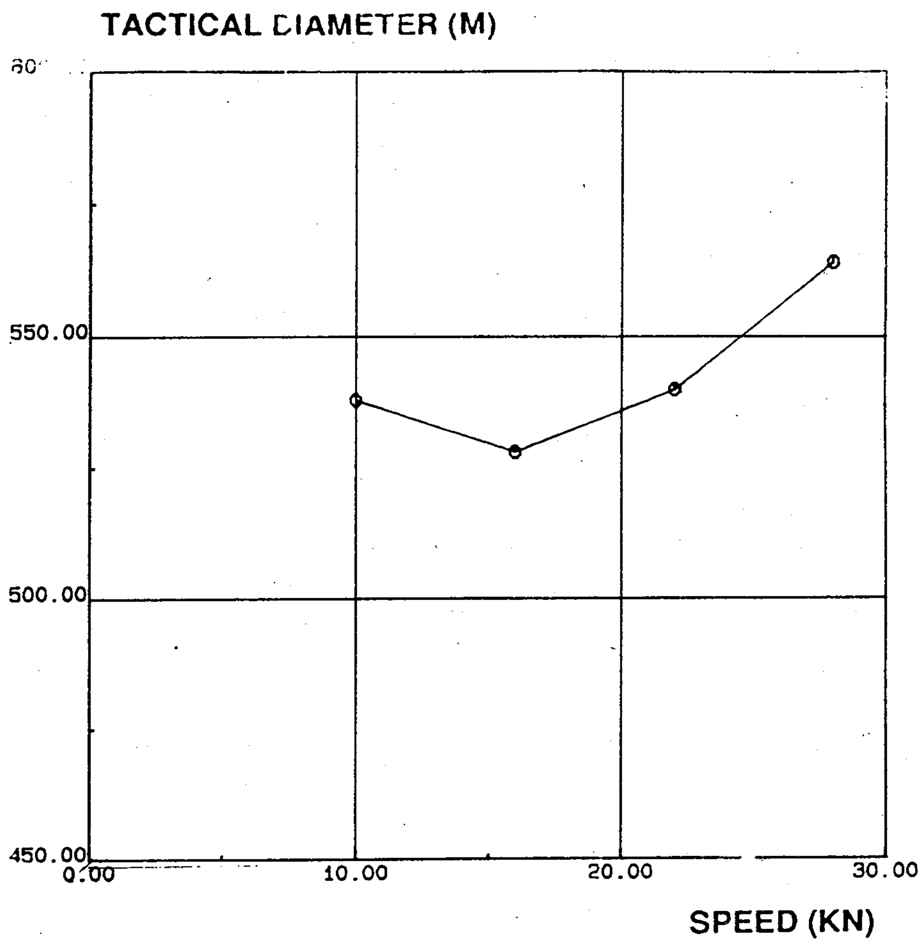

Fig. 14. Speed influence on the tactical diameter

4.3 Variation of rudder arrangement

A systematic variation of the rudder area was made and the different rudder alternatives were entered into the program and tested. The original rudder was designed with a relative rudder area (total rudder area divided by the product of length and draught) of 2.5 per cent, which can be considered to be fairly normal for this size of ship. The others tested here were given relative areas of 2, 3, 3.5 and 4 per cent respectively. All of them were designed with the same planform i.e. the same aspect ratio.

For all of them the same propeller was used, which meant that the diameter of the propeller race over the rudder was unchanged.

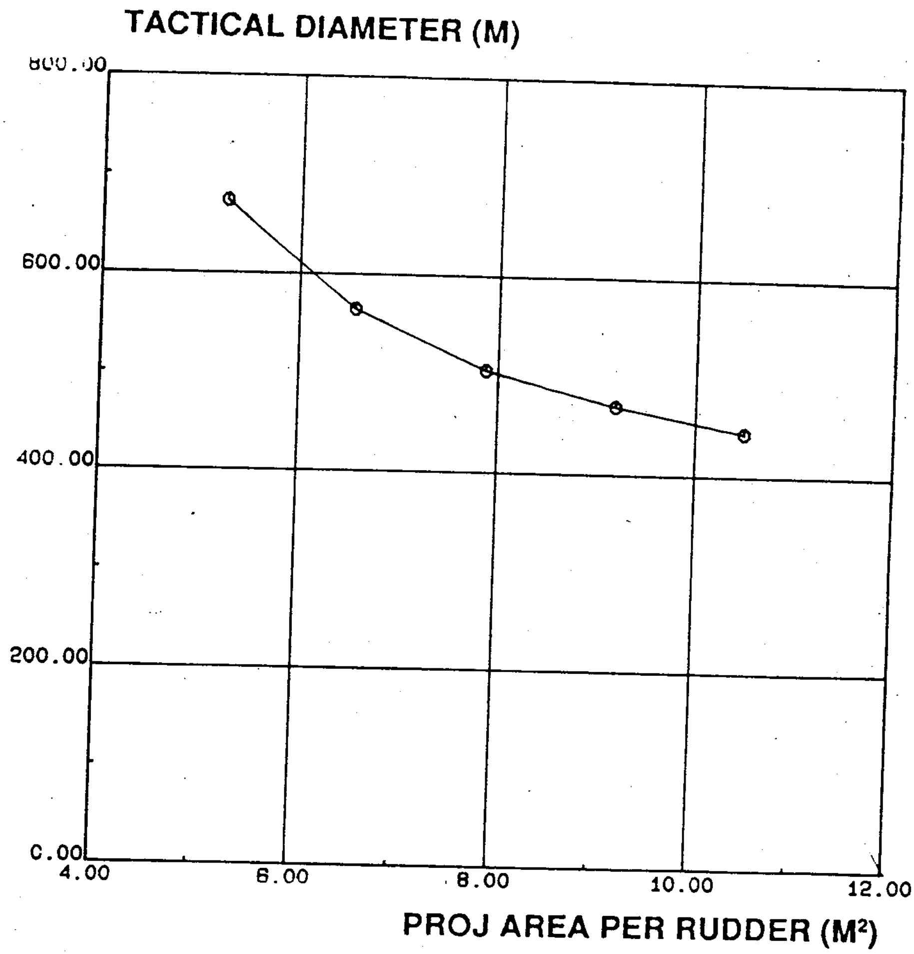

Fig. 15. Tactical diameter for different rudder areas

As is shown in Fig 15 the effect of increasing the rudder area (per rudder) to more than, say, the eight square metres will affect the steering ability, considering the tactical diameter, only marginally, while on the other hand, going in the other direction, a reduction will reduce the steering ability significantly.

The effect of the latter is extensive, as is illustrated in Fig 17. A design with the rudder covering the propeller completely (100 per cent) will provide a tactical diameter that is only about 60 per cent of that with the rudder applied completely outside the race (0 per cent), see Fig 16.

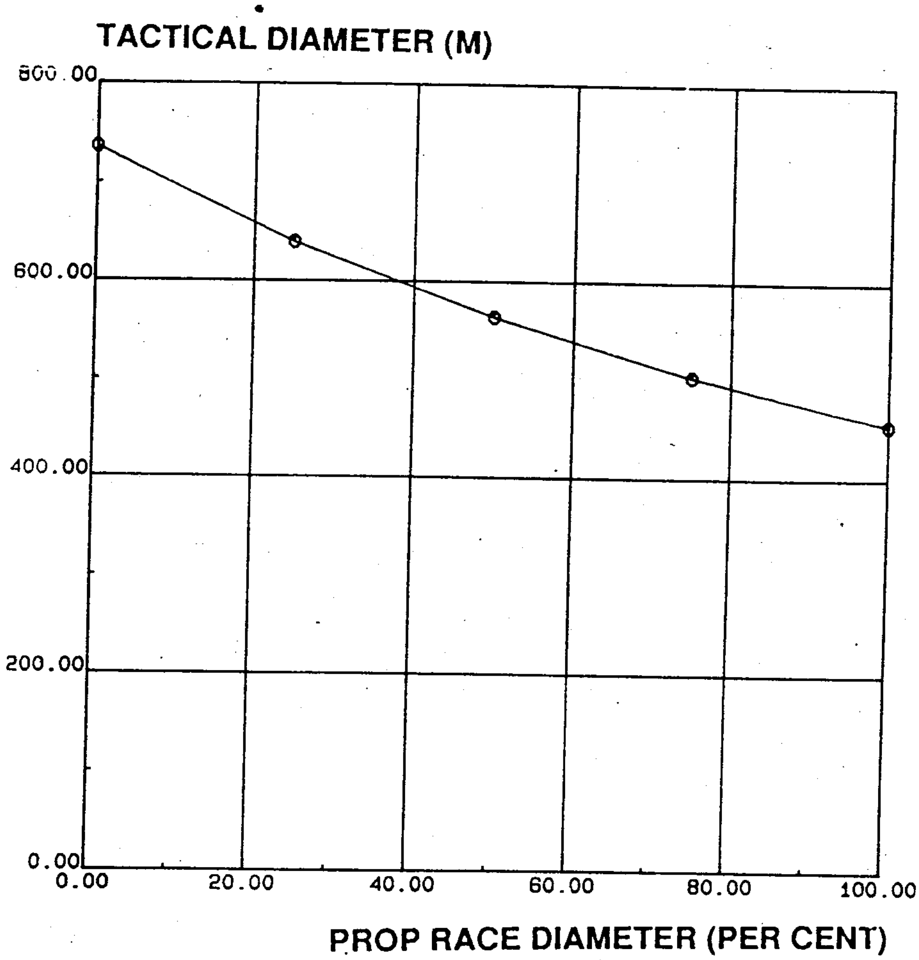

Fig. 16. The effect of lateral position of rudder relative the propeller on the steering ability

4.4 Variation of the vertical centre of gravity

It is in many cases difficult to calculate, in advance, the exact vertical location of the centre of gravity and thereby the metacentric height. The rolling behaviour when manoeuvring in calm sea might not be very important. However, at higher speeds and with rapid rudder motions quite extensive roll angles might be achieved.

In this particular case a vertical centre of gravity of 1.63 m above the water line and a GM-value of 1.4 m are assumed.

Varying the VCG from 1.33 degrees to 2.53 will entail a variation of GM from 1.7 down to 0.5 m respectively. The effect of this is illustrated in Figs 17-18, the former showing the roll angles in the different phases of a turning circle and the latter the same for a 10/10 and a 20/20 deg zig zag manoeuvre.

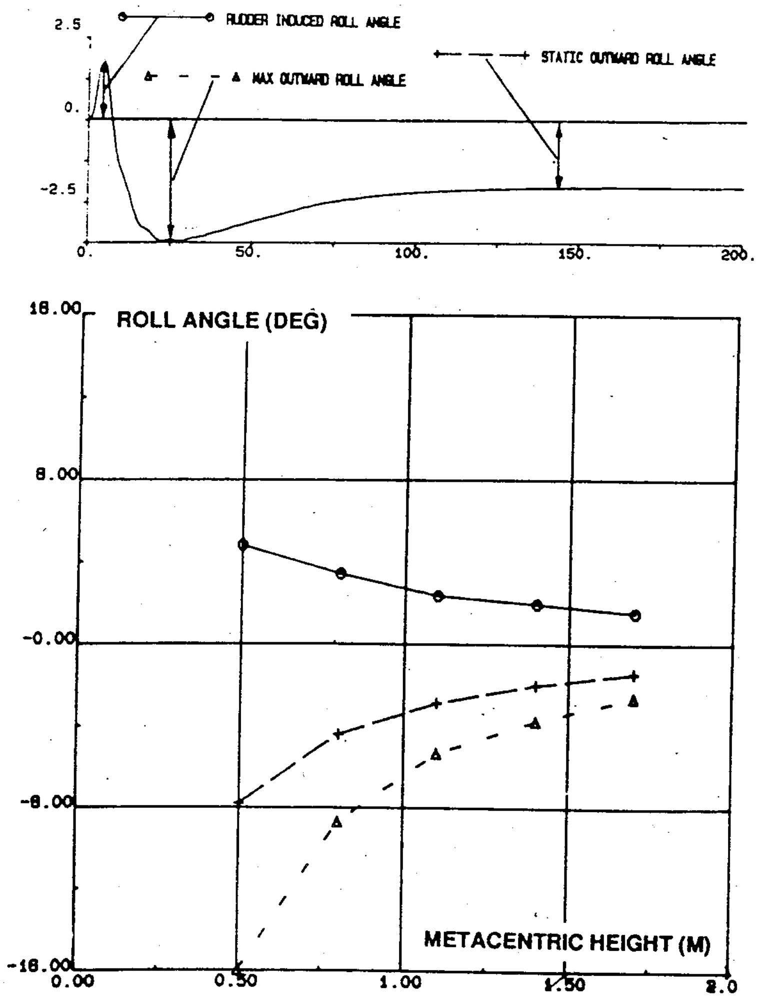

Fig. 17. Roll angles in a turning circle

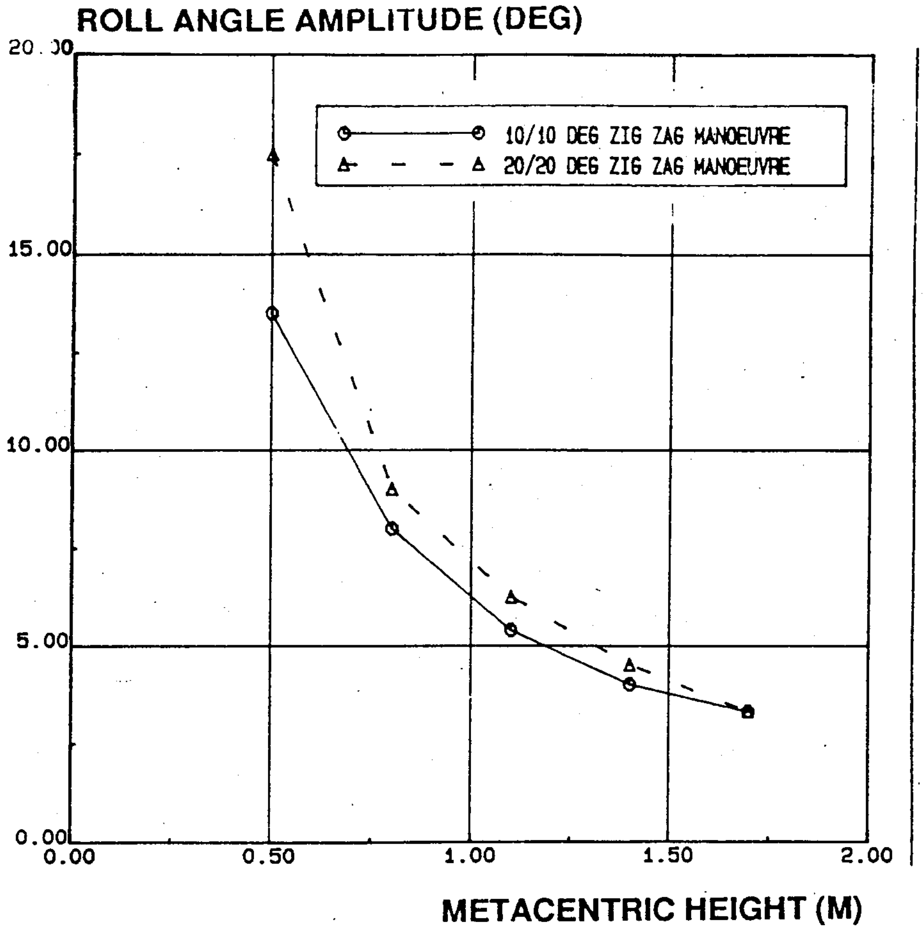

Fig. 18. Roll angles in 10/10 and 20/20 deg zig-zag tests

5. CONCLUSIONS

The simulation technique is a cost effective and powerful tool when investigating manoeuvring properties of different kinds of ships. It can be used separately, as is shown in this paper, and it can be used combined with model tests.

The simulation technique is a useful way of choosing between different design alternatives in an early design phase.

The program NAVMAN is believed to serve as an effective device in the design of new ships or when modifying already existing vessels. It may not provide results with fully the same accuracy as model tests do, but on the other hand it will enable the user to define the manoeuvring properties within short time limits.

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APPENDIX A

L	= length between perpendiculars
B	= max beam
B_{WL}	= max beam at water line
T_A	= draught, aft
T_F	= draught, fore
T_i, $i=0...10$	= local draught at sections 0. to 10
∇	= actual displacement
∇_F	= full load displacement
A_{skeg}	= skeg area
x_G	= longitudinal centre of gravity
z_G	= vertical centre of gravity
k_{xx}	= roll radius of gyration
k_{zz}	= yaw radius of gyration
BR	= botton rise at section 5
BK	= bilge keels or not
GM	= metacentric height
n_{GZ}	= number of GZ-values
φ_{GZi}, $i=1,...n_{GZ}$	= roll angles for given GZ-values
GZ_i, $i=1$, N_{GZ}	= GZ values for given roll angles
n_{rud}	= number of rudders
A_r	= total area per rudder
A_{rh}	= horn area per rudder
h_r	= height of rudder at rudder stock
h_{pr}	= height of propeller race over rudder
$\dot{\delta}$	= rudder rate
λ_N	= geometrical yaw lever arm of rudder
λ_K	= geometrical roll lever arm of rudder
n_p	= number of propellers
D	= propeller diameter
P/D	= pitch ratio
L/S	= vertical angle of shaft
H	= vertical angle between waterline and shaft
n_d	= propeller rate at max continuous rating