SEAKEEPING CHARACTERISTICS OF SWATH VESSELS

Ir. R.P. Dallinga

Maritime Research Institute Netherlands (MARIN)

ABSTRACT

Compared with conventional monohulls, SWATH type vessels offer great potential in terms of superior seakeeping characteristics. In the last decades this has stimulated research into SWATH hydromechanics and development of practical design tools.
Some of the basic understandings of SWATH hydromechanics are illustrated by comparing the hydrodynamic characteristics of a 2847 tonne SWATH vessel with a monohull of the same displacement. Special aspects of SWATH design like the design of stabilizing fins are dealt with. The differences observed in the motion characteristics of the two hulls are given an interpretation in the light of the wave climate prevailing at the North Sea.

1. INTRODUCTION

The economical efficiency of an oceangoing vessel is governed by the initial capital investment, the operational costs and the benefits in terms of achieving the objectives of the design. The complexity of this problem makes it very difficult to make a straightforward comparison between a SWATH and a monohull; a particular design requirement often yields SWATH and monohull designs which are not very comparable as to the main dimensions or displacement.

In the present investigation the comparison is based on vessels with the same displacement. In practice this will mean that the monohull has a relatively large payload; the SWATH has a relatively large deck area.
The SWATH hull form is the well-known DTNSRDC 6A design described by C.M. Lee [1]; basic characteristics of the vessel are shown in Table 1 and Figure 1. The characteristics of the (hypothetical) 100 m monohull are representative for a contemporary frigate hull form.

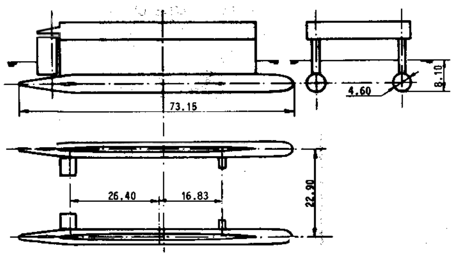

Fig. 1. Main particulars of swath

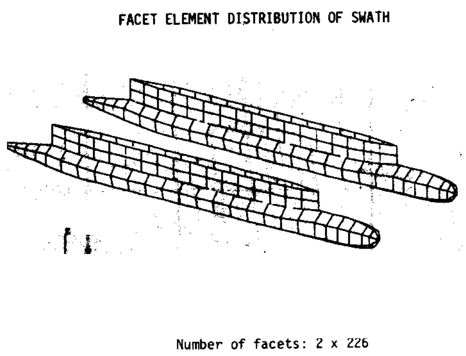

Fig. 2 Facet element distribution of swath

Table 1

MAIN PARTICULARS SWATH		
Length of main hull	m	73.15
Length at waterline	m	52.50
Hull spacing (centre lines)	m	22.90
Draft	m	8.10
Diameter main hull	m	4.60
Displacement	tonne	2847
Waterline area	m^2	193.90
Transverse metacentric height	m	2.90
Longitudinal metacentric height	m	6.80
MAIN PARTICULARS MONOHULL		
Length between perpendiculars	m	100
Breadth	m	14.4
Draft	m	4.7
Displacement	tonne	2847

The comparison is based on the assumption that the motion characteristics can be dealt with by linear seakeeping theory. This makes it possible to treat the problem of determining the wave induced forces separately from the problem of determining the motion induced hydrodynamic reaction forces. The motion characteristics were derived from the zero-speed characteristics of the hulls by assuming that the wave induced forces and hydrodynamic reaction forces are not affected by forward speed; in the latter only the Doppler shift in the oscillation frequency due to forward speed is accounted for.

2. CHARACTERISTICS OF THE UNAPPENDED HULLS

The basic zero-speed characteristics of the two alternative unappended hull forms were calculated by means of a computer program based on linear potential theory; the element distribution used to schematize the SWATH hull is shown in Figure 2. Viscous or lift effects were neglected in the calculations.

The results of the calculations are the wave induced forces and the hydrodynamic reaction forces in terms of added mass and wave making damping at zero speed.

Wave induced forces

In the wave induced forces contributions from the pressure field in the undisturbed wave (the 'Froude-Krylov' component) and the pressure field from the diffraction effects were discerned. In the vertical modes the first force component is associated partly with the geometry of the waterline; the second component is associated with the volume and shape of the submerged part of the hull.
Figures 3 to 6 show the magnitudes of the wave induced forces in the heave and pitch mode. For both the monohull and the SWATH the Froude-Krylov component dominates the wave induced forces at low frequencies; at higher frequencies the total force is a complicated mix of both compo-

nents, often acting in opposite direction. The humps in the diffraction component can be associated with the wave length and the distribution of the volume along the length of the hull; experience with various SWATH hull forms learns that the height of the peaks in the excitation forces can be influenced strongly by adopting a favourable hull form.
The obvious difference between the two hull forms resides in the magnitude of the total excitation, especially relevant in the important wave frequency range between 0.5 and 1 rad/s.

Although the heave and pitch excitation for both hull forms differ in magnitude their character was similar; this is not the case for roll, see Figures 7 and 8. Contrary to the monohull the excitation of the SWATH is dominated strongly by diffraction effects. The roll excitation of the monohull is quite modest when compared to that of the SWATH.

Hydrodynamic reaction forces

The forces acting on the hull as a result of the motion response are expressed by an added mass and a damping term. Figures 9 to 14 compare the results of the calculations for the heave, roll and pitch modes. It is shown that for the heave and pitch modes the hydrodynamic reaction forces of the SWATH are characterized by a relatively small added mass and very small wave making damping. For roll both the added mass and damping are substantially greater than that observed for the monohull.
Noteworthy are the interaction effects between the hulls at higher oscillation frequencies; experience with experimental results shows that potential theory tends to overestimate interaction effects.

Restoring forces and natural periods

The restoring forces govern, together with the structural mass and added mass, the natural frequencies in the vertical modes. The limited waterline area of the SWATH affects particularly the restoring forces in heave and pitch; in most cases the longitudinal stability of a SWATH is only slightly larger than the transverse stability.

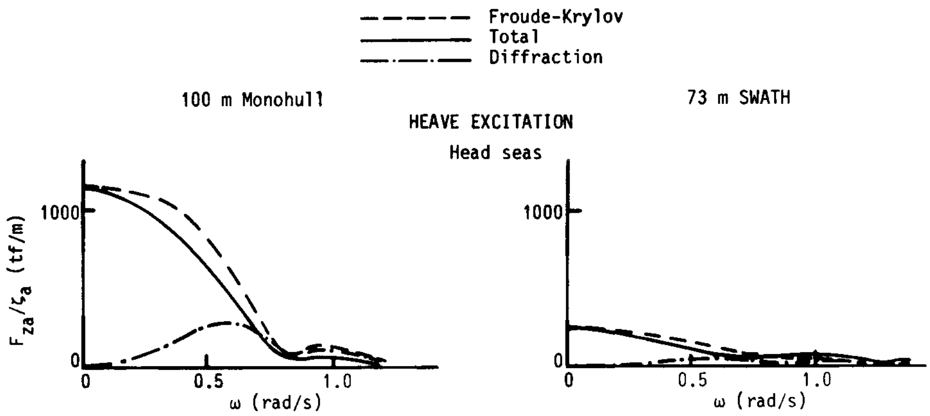

Fig. 4

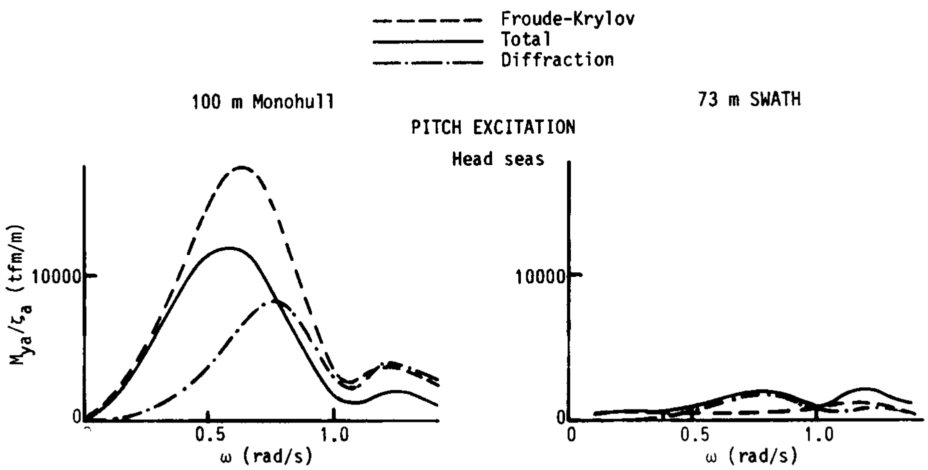

Fig. 6

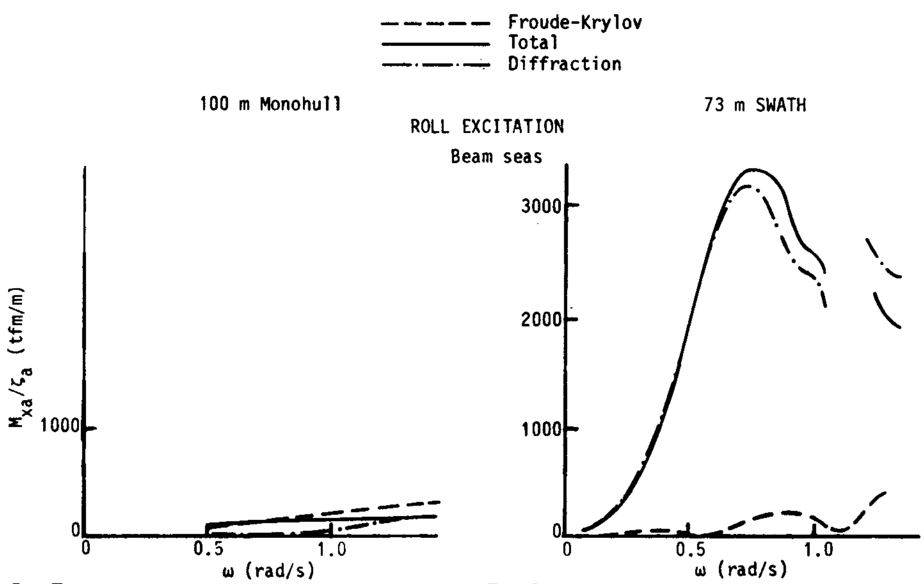

Fig. 7

Fig. 8

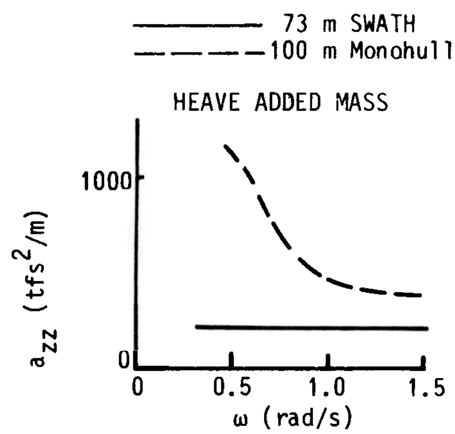

Fig. 9

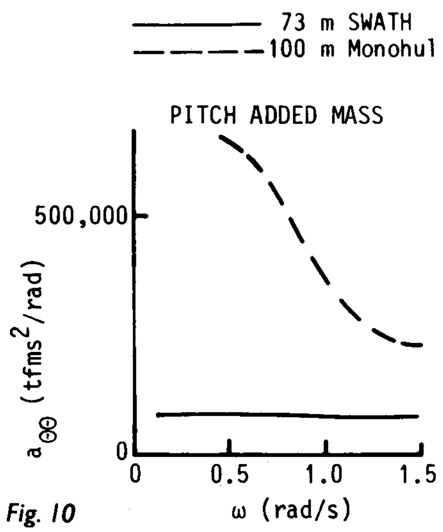

Fig. 10

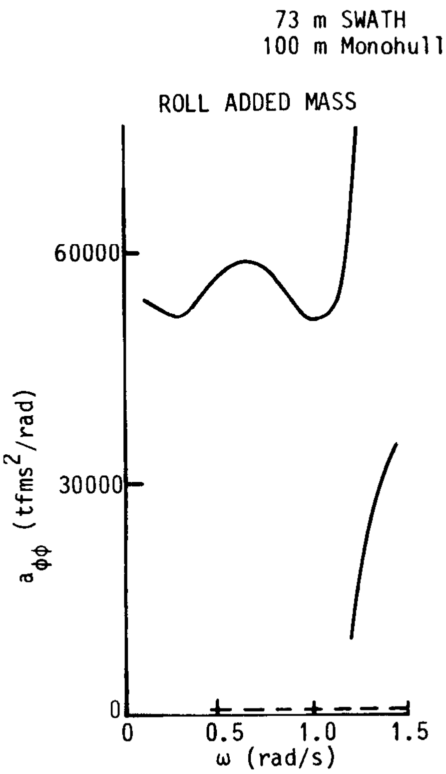

Fig. 11

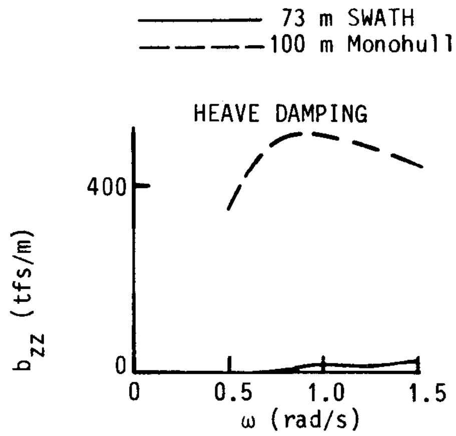

Fig. 12

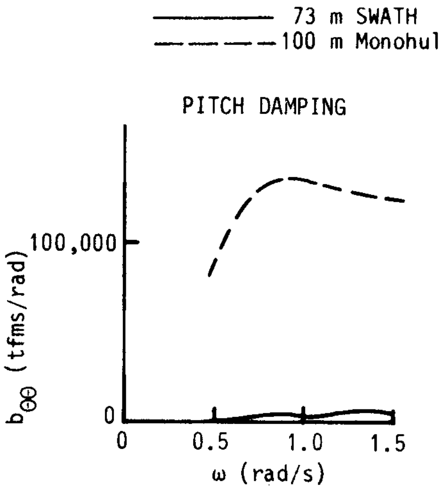

Fig. 13

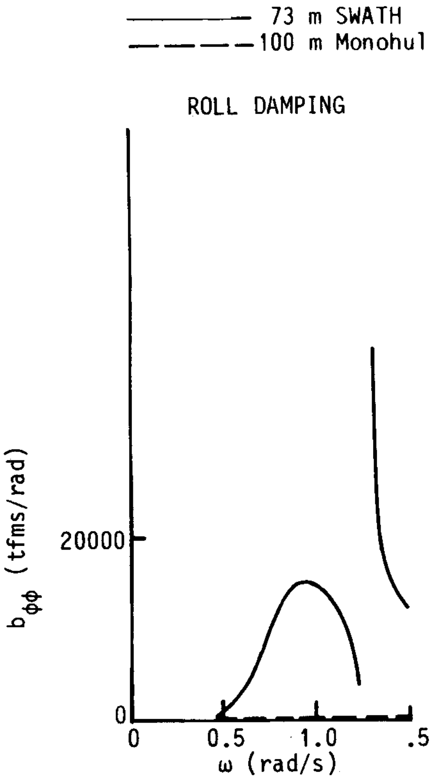

Fig. 14

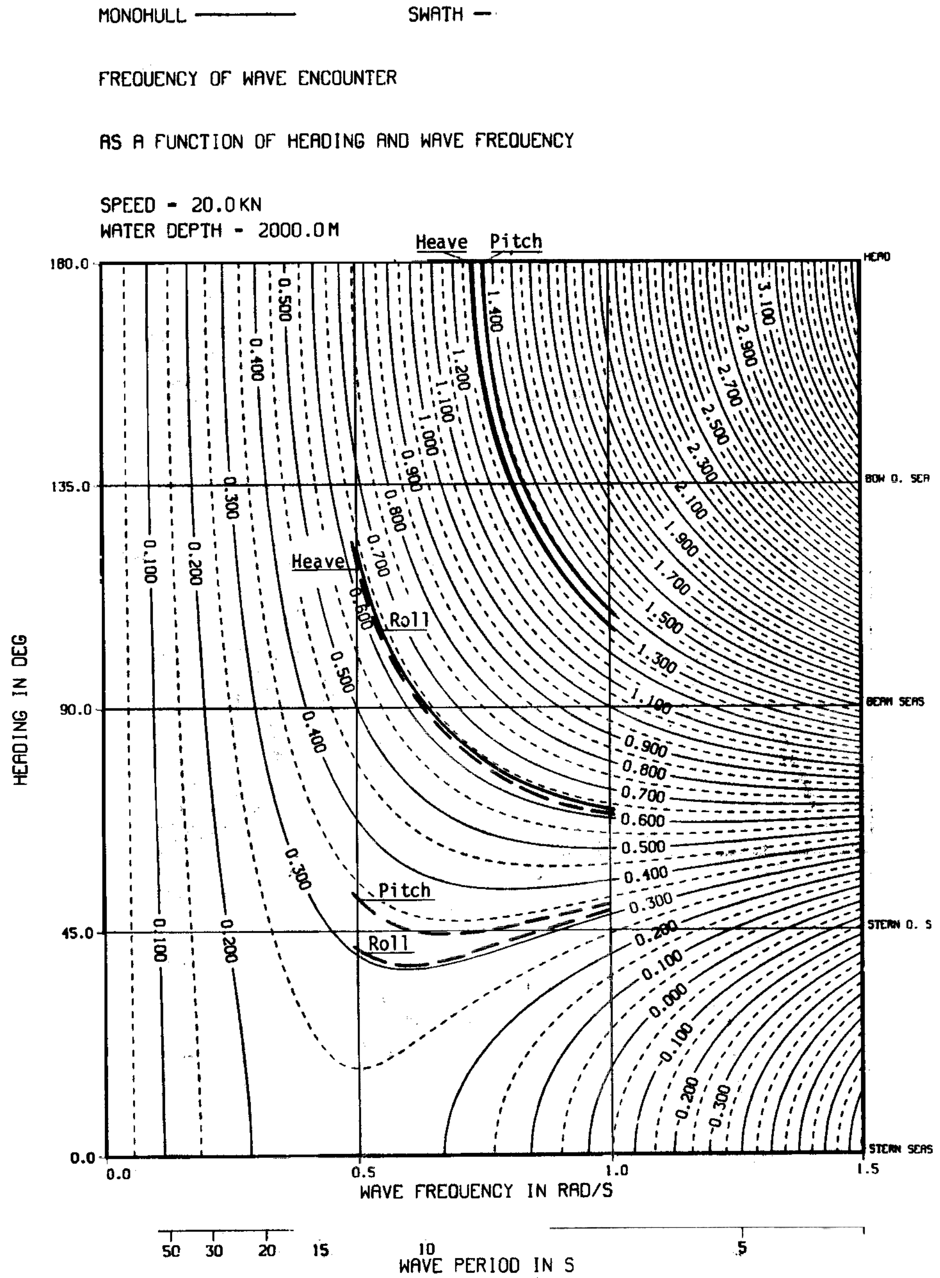

Fig. 15 Frequency of wave encounter as a function of heading and wave frequency

The following table summarizes the natural frequencies of the two hulls, together with the relative damping (in fractions of the critical damping) in the various modes.

	SWATH		Monohull	
	ω_n [rad/s]	μ [–]	ω_n [rad/s]	μ [–]
Roll	0.31	0.0003	0.68	0.0036
Heave	0.63	0.0080	1.31	0.2600
Pitch	0.33	0.0004	1.34	0.2300

Only the heave and pitch responses of the monohull show considerable damping. In the remaining cases a relatively high response may be expected if the freqency of wave encounter is close to the natural frequency of the mode concerned.
Considering the wave frequency range between 0.5 and 1 rad/s as the dominant wave frequency range (disregarding long period swells) it may be concluded that at zero speed only the heave motions of the SWATH are subject to dynamic amplification effects; the monohull experiences unfavourable tuning in the roll mode. At non-zero speed the monohull experiences unfavourable tuning with the heave and pitch modes in head and bow quartering seas and roll in beam seas; Figure 15 shows that the SWATH meets these conditions in beam and stern quartering seas.

Motion response of the unappended hull
Figures 16 to 21 show the motion response of the unappended hulls in head and beam seas.
The lightly dampened modes of motion are characterized by sharp resonance peaks. The benefits of the SWATH design at non-zero speed are readily recognized; in the wave frequency range of practical interest the heave, roll and pitch motions are considerably smaller than those observed for the monohull.

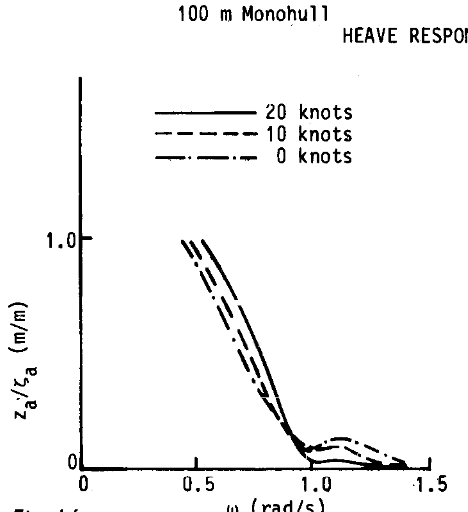

Fig. 16

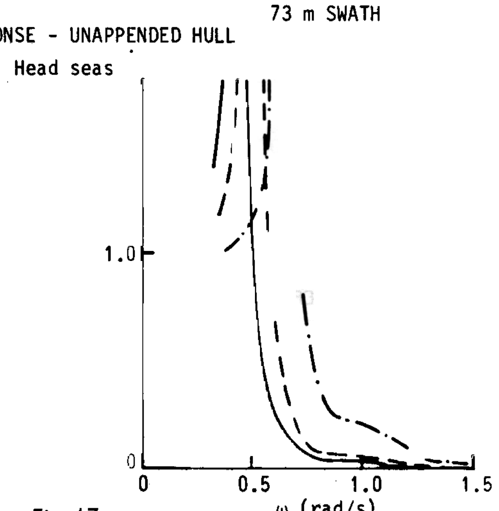

Fig. 17

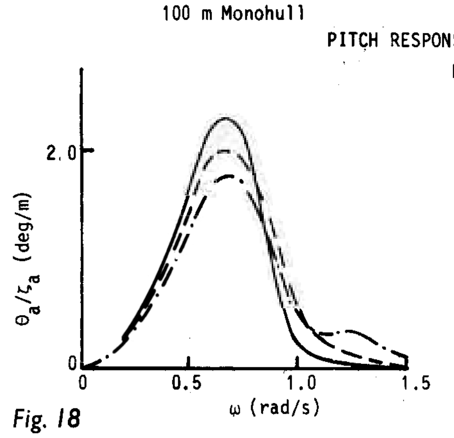

Fig. 18

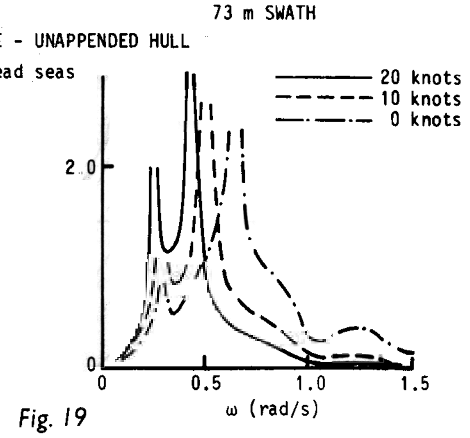

Fig. 19

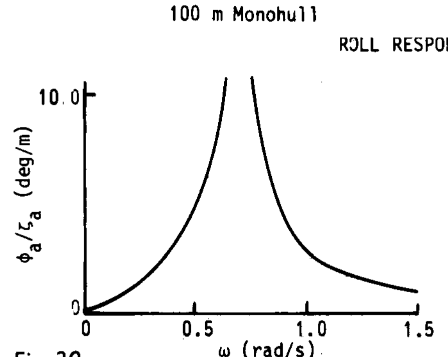

Fig. 20

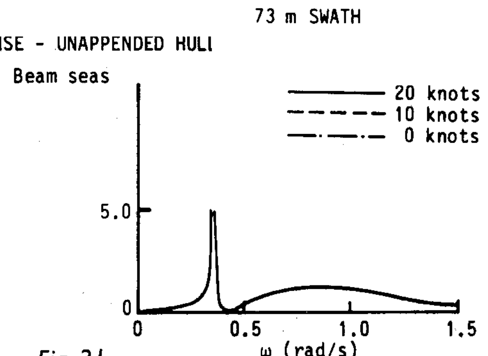

Fig. 21

3. STABILIZING FINS

In practice lift and drag forces acting on the hull limit the motion amplitudes in resonant conditions; because these forces are often relatively small, appendages are often beneficial in an effort to increase the damping. The use of (active) fin stabilizers is common practice on passenger vessels and frigates.
Stabilizing fins operate in a flow field which may be regarded as the sum of a steady (non-homogeneous) flow as a result of forward speed, the incident and diffracted waves and the motion response of the vessel. In general these forces manifest themselves in the wave induced forces, the hydrodynamic reaction forces and the restorring forces.
State-of-the-art computer programs do not allow a detailed analysis of the flow field in the proximity of the hull oscillating among waves. For this reason, the starting point for the analysis of the forces acting on the fins will be the (sometimes crude) assumption that they operate in an undisturbed uniform flow supplemented with orbital motions when considering wave induced forces or the (local) motion amplitudes when considering the hydrodynamic reaction forces. For reasons of simplicity only the lift forces will be dealt with. Knowledge of the angle of attack makes it possible to make an estimate of the related forces:

$$F_a = \tfrac{1}{2} \rho V^2 . A_f . \frac{\delta C_L}{\delta \alpha} . \alpha_a$$

in wich
F_a = lift amplitude
ρ = specific density of (sea)water
V = forward speed
A_f = fin area
$\frac{\delta C_L}{\delta \alpha}$ = lift slope
α_a = amplitude of the angle of attack.

Apart from disturbing the flow field the geometry of the hull affects the lift characteristics of the fins; in addition the lift forces on the fins show 'carry-over' to the hull. Lee [1] describes an approach based on slender body theory to calculate these interferences between a fin and a slender body.
Research on hydrofoil craft has shown that also free surface effects have a considerable influence on the lift characteristics of stabilizing fins. In this report reference is made to work by Van Walree [2]. In addition fin-fin interferences can be important; McCreight [3] quotes data from Lloyd [4] and Cox [5] which can be used to make an estimate of the interferences; in the present work interferences are neglected.

In the absence of a practical numerical tool to describe the flow along a vessel oscillating at non-zero forward speed among waves the above approaches are helpful in early stages of the design; experience with the correlation between the results of theoretical calculations and model tests [6] indicates that physical experiments are essential to obtain a reliable final prediction.

Angle of attack

When considering the wave induced forces acting on a horizontally oriented fin the linearized angle of attack α_a is given by:

$$\alpha = \dot{z}/V$$

in which

$\dot{z}$ = (local) vertical component of the orbital motion in the undisturbed wave
V = ship speed.

The effective angle of attack follows from:

$$\alpha_e = \dot{z}/V + \alpha_c + \Theta$$

$\dot{z}$ = the local vertical motion of the fion as a result of heave, roll and pitch motions,
α_c = fin angle as a result of active fin control (reacting on, for instance, roll and pitch and their time derivatives),
Θ = pitch angle.

Following the above equations it becomes clear that the wave induced forces and the passive part of the hydrodynamic reaction forces (damping) are proportional to the forward speed. The active fin control introduced a damping component which is proportional to the square of the forward speed. Also the restoring forces due to the pitch angle or active fin control are proportional to the square of forward speed.

Fin characteristics

The geometry of the fin arrangement of the SWATH is shown in Figure 1. In agreement with the procedure adopted by Lee [1] the empirical expression derived by Whicker and Fehlner [7] for the lift slope of low aspect wings is used to calculate the basic characteristic of the wing. The adopted effective aspect ratio is:

$$A_e = (r_0 - r/r_0)/c$$

in which
A_e = effective aspect ratio
r_0 = distance fin tip to body axis
r = body axis
c = average chord.

The lift slope of the wing alone follows from:

$$\frac{\delta C_L}{\delta \alpha_W} = 1.8 \star \pi \star A_e / \left(1.8 + (A_e + 4)\right) [\text{rad}^{-1}]$$

The total lift in deeply submerged condition becomes:

$$\frac{\delta C_L}{\delta \alpha} = (K_{W(B)} + K_{B(W)}) \cdot \frac{\delta C_L}{\delta \alpha_W} \quad [\text{rad}^{-1}]$$

in which

$K_{W(B)}$ = factor representing the lift induced by the body on the wing
$K_{B(W)}$ = factor representing the 'carry-over' of lift from the foil to the body.

The above interference factors are indicated in Figure 22. The lift slope was corrected for free surface effects according to [2]; it was found that the two-dimensional correction to the bound vortex dominated the result. This correction is shown in Figure 23.
The following table summarizes the results of the calculations for both fins:

Wave induced forces

In those cases where the wave induced forces acting on the hull are small a significant contribution may be expected from the stabilizing fins. Figures 24 to 26 indicate

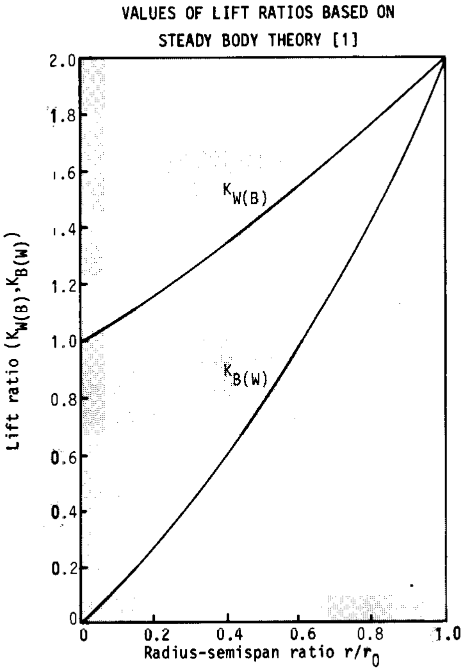

Fig. 22 Values of left ratios based on steady body theory

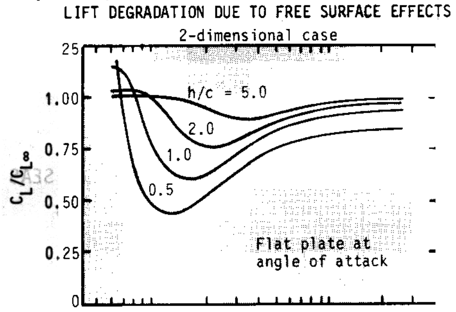

Fig. 23 Lift degradation due to free surface effects.

		Fwd fin	Aft fin
Area	[m]	8.1	24.0
Chord	[m]	2.6	4.5
Span	[m]	3.1	5.4
Body radius	[m]	2.3	2.3
Fin mounted on small diameter body in an infinite medium; Lee [1]			
Effective aspect ratio	[-]	1.54	1.70
Lift slope wing only	[rad^{-1}]	2.01	2.17
Lift slope wing in proximity hull	[rad^{-1}]	2.51	2.93
'Carry-over' from wing on hull	[rad^{-1}]	0.90	1.48
Total effective lift slope	[rad^{-1}]	3.41	4.41
Free surface effects; Van Walree [2]			
Lift degradation	[%]	15	9
Total effective lift slope	[rad^{-1}]	2.90	4.0

For the monohull two 7.3 m^2 fins at an angle of 45 degrees were accounted for; an effective lift slope of 4 rad^{-1} was adopted.

the relative magnitude of the wave induced forces on the hull and the fins; the heave and pitch modes are considered for the SWATH hull; the roll mode for the monohull. The results show that the contribution from the fins is far from negligible in all cases.

Hydrodynamic reaction forces

Figures 27 to 29 show the relative magnitude of the contribution of fins and hull for the foregoing cases; the fins meet there purpose in terms of a strong increase of the damping.

Motion response of the appended hulls

The following table summarizes the revised values for the natural periods and dimensionless damping for the case of passive fins. It shows that the presence of fins increases the damping values quite considerably.

	SWATH		Monohull	
	ω_n [rad/s]	μ [–]	ω_n [rad/s]	μ [–]
Roll	0.31	0.100	0.68	0.260
Heave	0.63	0.183	1.31	0.260
Pitch	0.45	0.430	1.34	0.230

The foregoing results were implemented in the equations of motion; the original (undampened) results are compared with the dampened values in Figures 30 to 33. Comparison with experimental results reported by Keuning [8] indicates that the prediction (based on potential theory calculations for the hulls supplemented only with estimates of the effects of the stabilizer fins) yields a very reasonable prediction of the motion characteristics for higher wave frequencies. In the lower wave frequency range resonant behaviour is overestimated by the adopted approach.

4. OPERABILITY ANALYSIS

Wind and waves

Wind and wind generated waves strongly affect the operability of oceangoing vessels. For this reason an operability analysis is not complete without account for their presence. Important environmental parameters in such an analysis are the spectral characteristics of the waves in storm conditions (wave height, characteristic period) in relation to the wind velocity and the persistence of storms. The natural variability of the environment within an 'invar-

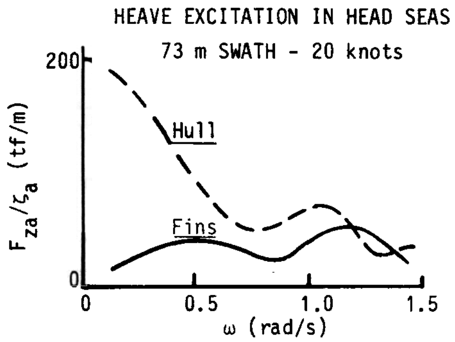

Fig. 24

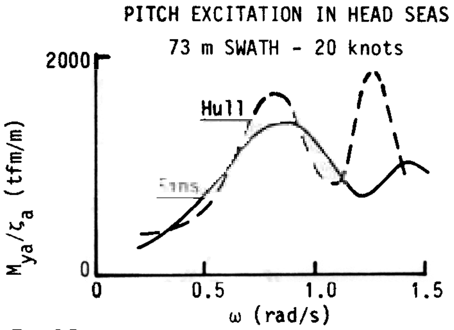

Fig. 25

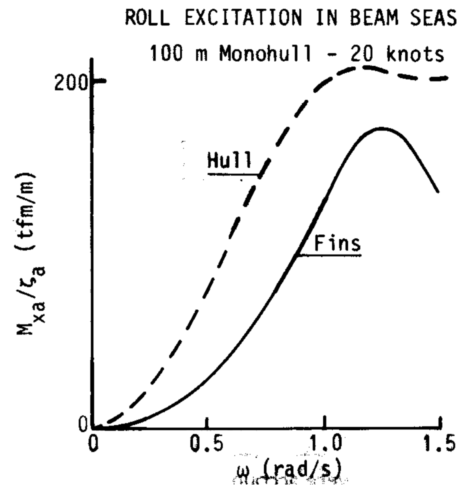

Fig. 26

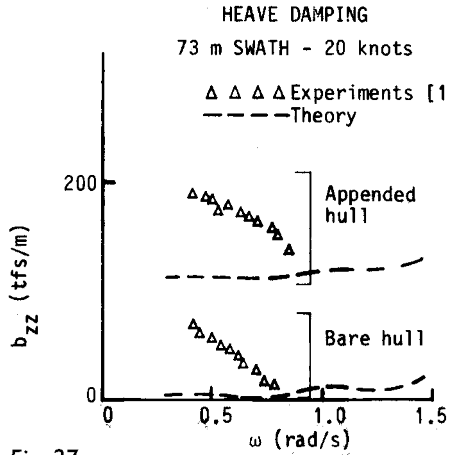

Fig. 27

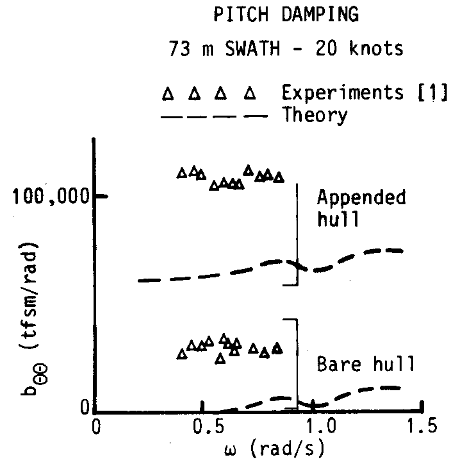

Fig. 28

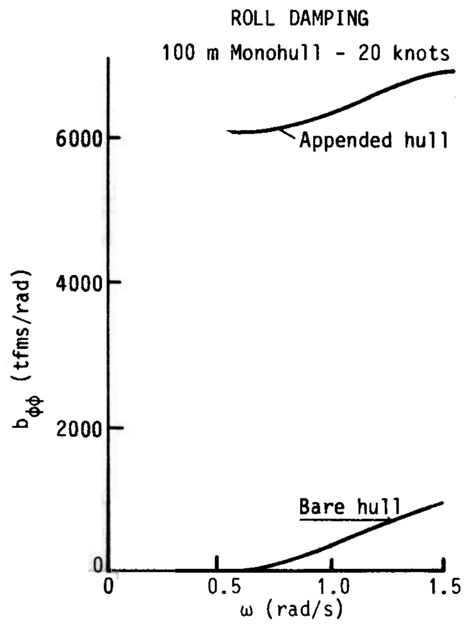

Fig. 29

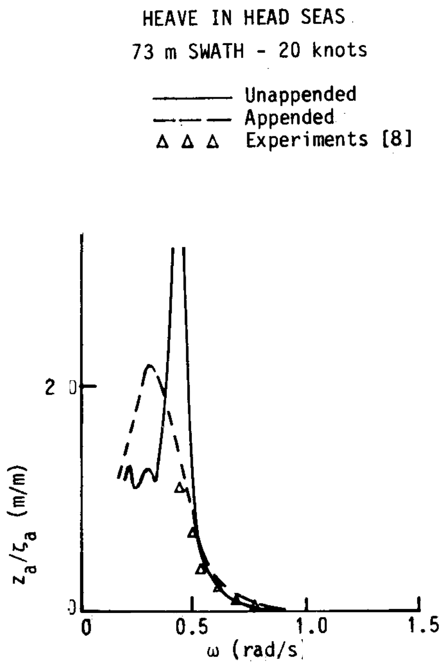

Fig. 30

iable climate implies that long-term statistics of these parameters are required for a reliable analysis.
In ocean engineering practice wind and wave data are often used in terms of a Beaufort number in which a direct relation between wind speed on one hand and wave height and wave period on the other hand is adopted. The table on the next page (see also Figure 34) gives some examples.
Although attractive because of its simplicity the single dimension of the climate description seriously affects the reliability of the results. Information from measurements and observations off shore has pointed out that the relation between wind speed and the various wave parameters is far more complicated than suggested by a Beaufort number for 'average' conditions. Figure 35 indicates the degree of variability of the wave height within a beaufort number on the North Sea [10].

A basic mechanism behind the scatter in the wind velocity and wave parameters is that higher wave conditions require a considerable time to achieve an equilibrium state with the wind speed, both in growth and decay. Equilibrium conditions are, as far as the higher wave conditions are concerned, seldomly achieved.
Apart from introducing scatter in the relation between wind speed and wave height the same mechanism introduces scatter in the relation between wave height and wave period. This is reflected in a well-

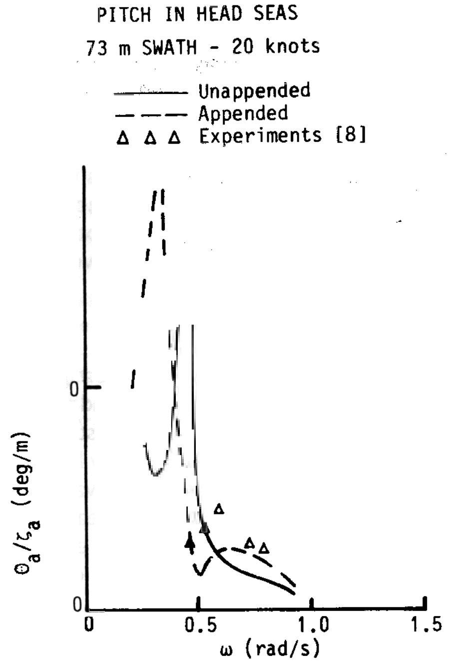

fig. 31

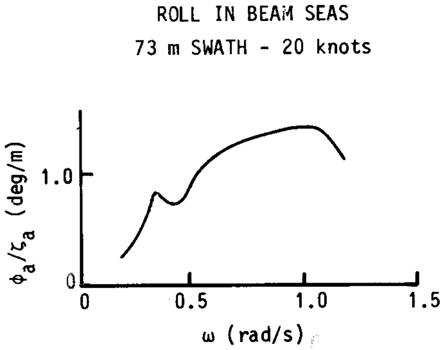

Fig. 32

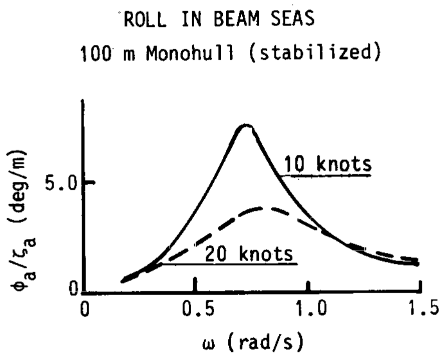

Fig. 33

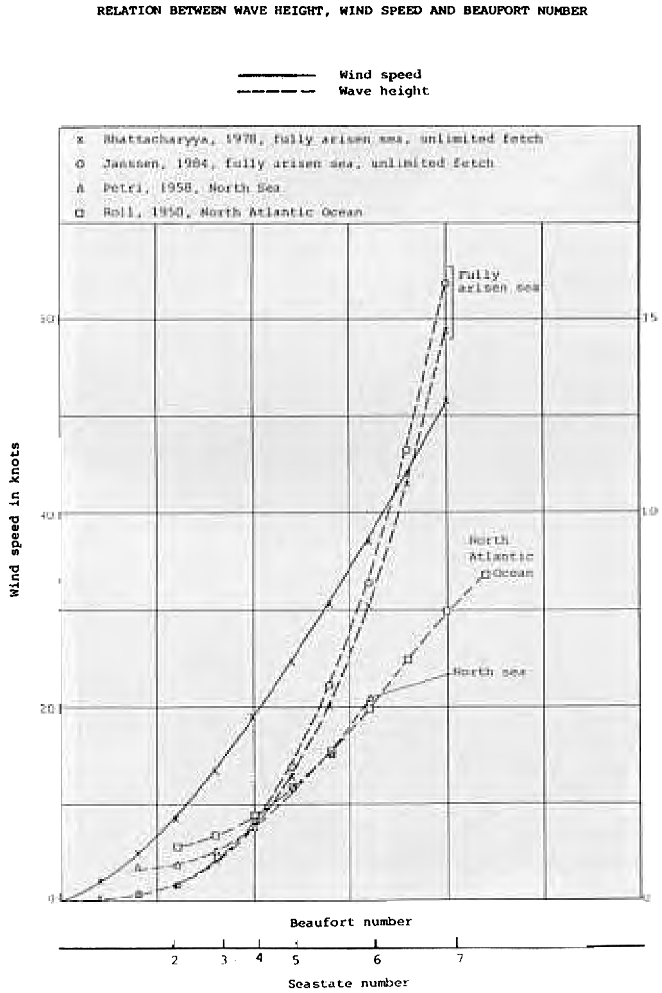

Fig. 34 Relation between wave height, wind speed and Beaufort number.

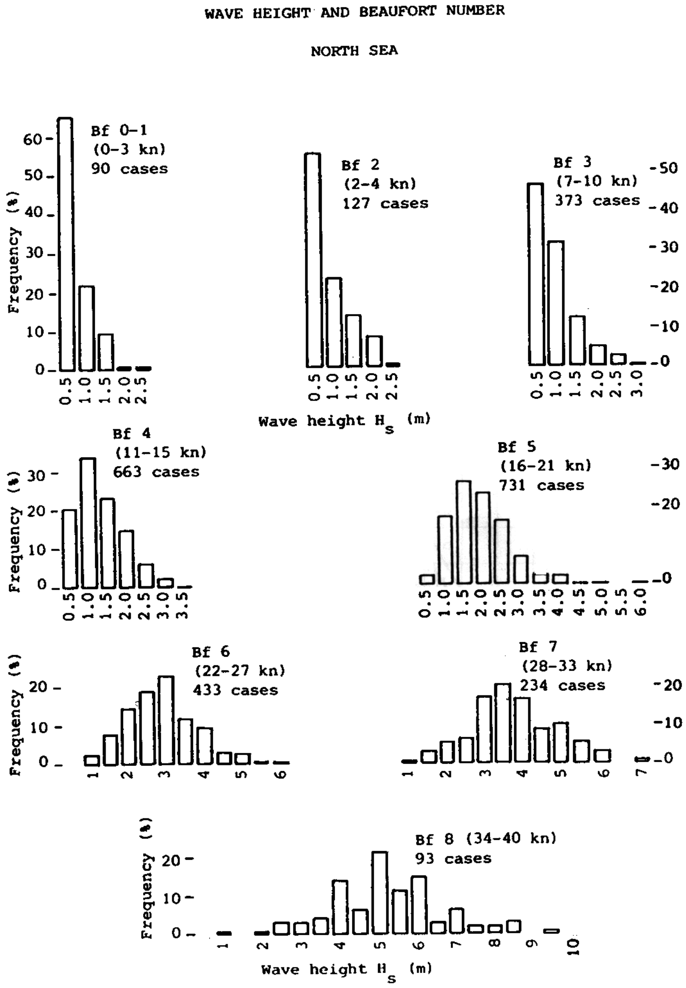

Fig. 35 Wave height and Beaufort number.

Beaufort No.	Wind velocity V_w (m/s)	Significant wave height: N. Atlantic Roll [9] H_s (m)	North Sea Petri [10] H_s (m)	Fully arisen Bhattacharyya [11] H_s (m)
2	2.6		0.9	0.15
3	4.4	1.40	0.9	0.40
4	6.9	1.70	1.3	1.00
5	9.8	2.15	1.9	2.01
6	12.6	2.90	2.9	3.20
7	15.7	3.75	3.7	5.15
8	19.0	4.85	5.2	7.58
9	22.7	6.20		10.73
10	26.6	7.45		14.73

know way to present wave statistics, the so-called wave scatter diagram. A source with worldwide information is provided in 'Global Wave Statistics' [13]. Janssen [12] describes a wave model in which a combined relation between wind speed, wave height and (peak = modal) wave period is used for the wind driven part of the wave spectrum. Figure 36 shows a scatter diagram for the North Sea in which the wind speed (derived from wave height and wave period) is indicated. It shows that the left-hand side of the scatter diagram is characterized by relatively high wind speeds; the right-hand side may be characterized as swell.

Criteria

Operability figures can be derived from the wave statistics by applying criteria for the maximum allowable motion response of the vessel. Generally these criteria are derivates of the basic motion components of the hull, for instance acceleration levels, the relative wave elevation at the bow or the added resistance or speed loss. The NORDFORSK study [14] provides guidelines for some applications.

In the present work only the vertical acceleration levels at the bow and the roll motions were taken into consideration. Figure 37 illustrates the results of this analysis. They confirm the potentials of the SWATH concept; the vertical accelerations at the bow and the roll motions of the SWATH are substantially lower than those of the monohull.

5. CONCLUSIONS

Regarding the results of the investigation discussed in this paper it is concluded that the hydromechanic characteristics of SWATH hulls are characterized by low excitation levels and low damping values in the vertical modes of motion, heave and pitch. Stabilizing fins are effective in increasing the damping to acceptable levels

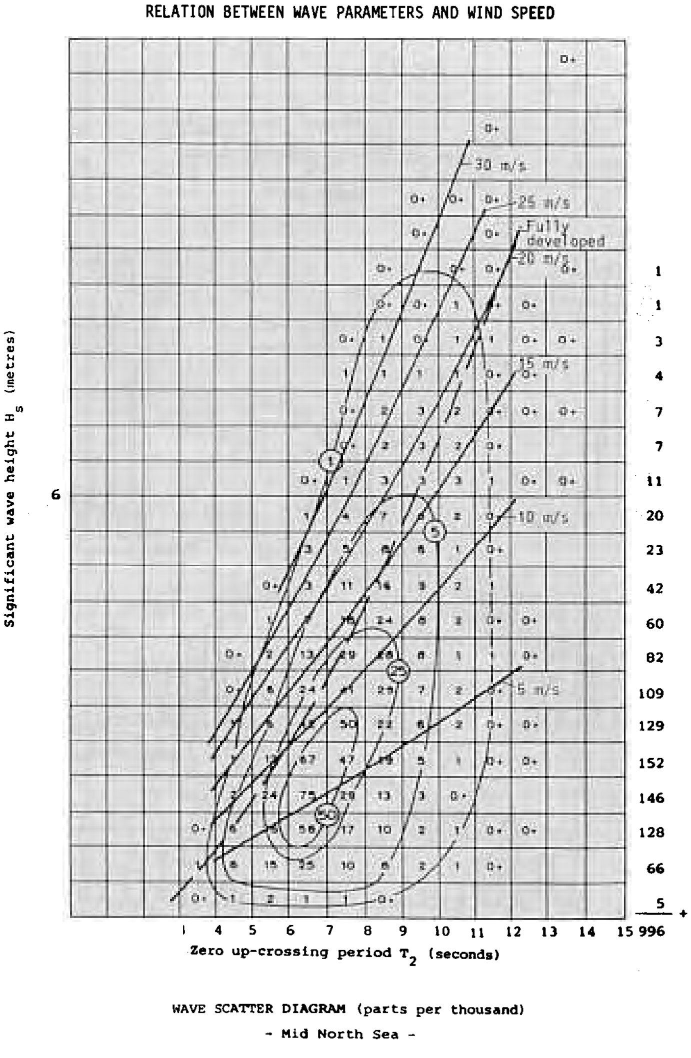

Fig. 36 Relation between wave parameters and wind speed

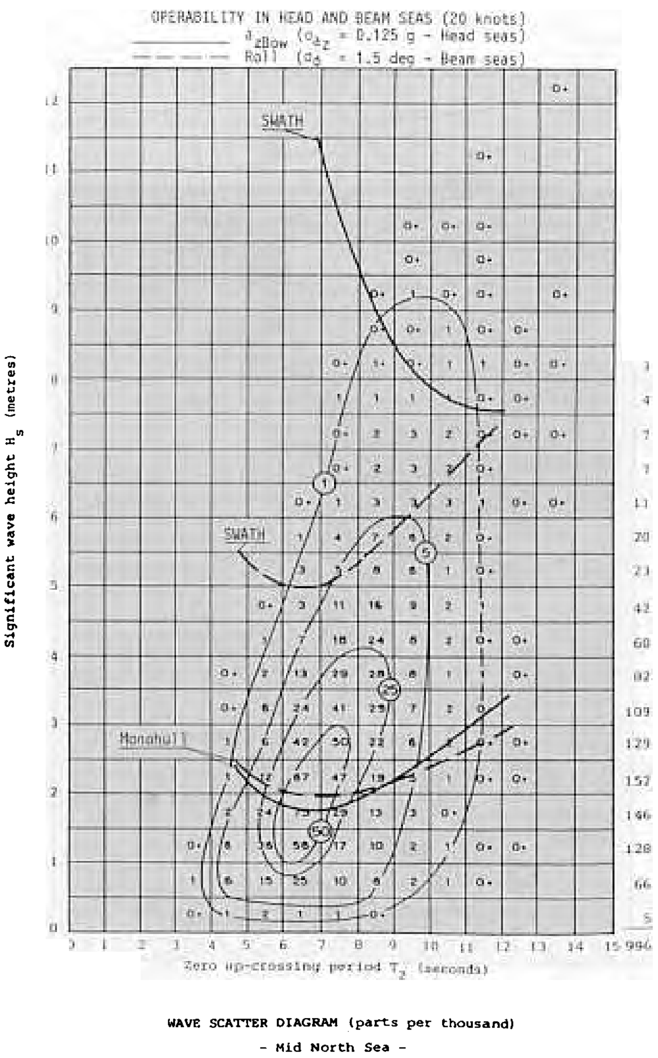

Fig. 37 Operability in head and beam seas (20 knots)

at non-zero speed. However, the low wave induced excitation implies that the contribution of the fins in the total excitation is far from negligible.

A numerical approach based on zero-speed potential theory for the hull supplemented with the effects of the stabilizing fins yields a reasonable prediction of the heave and pitch response in non-resonant conditions.

Comparing two vessels of a similar displacement (a SWATH and a monohull) the SWATH shows superior seakeeping characteristics because of its low acceleration levels and small roll angles.

References

[1.] Lee, C. M.: Theoretical prediction of motion of small-waterplan-area, twin-hull (SWATH) ships in waves. DTNSRDC Report 76-0046.

[2.] Walree, F. van: Resistance prediction method for hydrofoil craft. Delft University of Technology, 1985.

[3.] McCreight, K. K.: Assessing the seaworthiness of SWATH ships. SNAME Transactions, 1987.

[4.] Lloyd, A. R. J. M.: Roll stabilizer fins: Interference at non-zero frequencies. Transactions RINA, Vol. 1127, 1975.

[5.] Cox, C. G. and Lloyd, A. R. J. M.: Hydrodynamic design basis for navy ship roll motion stabilization. Transactions SNAME, Vol. 85, 1977.

[6.] Dallinga, R. P., Graham, R. and Huijsmans, R. H. M.: Development of design tools for the prediction of SWATH motions. 17th Symposium on Naval Hydrodynamics, The Hague, 1988.

[7.] Whicker, L. F. and Fehlner, L. F.: Free stream characteristics of a family of low-aspect, all-movable control surfaces for application to ship design. DTNSRDC Report 933, 1958.

[8.] Keuning, J. A.: Force oscillation tests and motion measurements with a small waterplane area twin-hull ship. Delft University of Technology, Ship Hydromechanics Laboratory, Report 533, December 1981.

[9.] Roll, H. U.: Höhe, Länge und Steilheit der Meereswellen im Nord-atlantik. Deutscher Wetterdienst, Seewetteramt, Einzelveröffentlichungen, Nr. 1, Hamburg, 1953.

[10.] Petri, O.: Statistik der Meereswellen in der Nordsee. Deutscher Wetterdienst, Seewetteramt, Einzelveröffentlichungen, Nr. 17, Hamburg, 1958.

[11.] Bhattacharyya, R.: Dynamics of marine vehicles. ISBN 0-471-07206-0, 1978.

[12.] Janssen, P. A. E. M.: An operational coupled hybrid wave prediction model. Journal of Geophysical Research, Vol. 89, pp. 3635-3654, 1984.

[13.] Global Wave Statistics. ISBN 0-946653-38-0.

[14.] NORDFORSK, Assessment of ship performance in a seaway. ISBN 87-982637-1-4.