THE STABILITY OF SHIPS IN WAVES; A COMPARATIVE STUDY OF MODERN HULL FORMS WITH LARGE B/T RATIO

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ABSTRACT

The variation of initial stability in waves has been studied for different hull forms with large B/T. The study was performed in regular following waves with close to zero encountering frequency as well as in regular waves with a frequency in resonance with parametric excitation of roll. The variation of restoring moment was calculated with a quasi-static approach taking into account the influence from the position of the wave profile and the ships vertical motions calculated with linear strip theory.
The study shows that both the sectional forms of the hull and the B/T ratio has a significant influence on the stability variation in waves.

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1 INTRODUCTION

Transverse stability is one of the most important parameters that must be taken into account in the ship design state. International criteria on stability put limits on the ships loading conditions and governs the choice of main dimensions of the hull both below and above the water line.

For ships with cargo of low density, for instance Ro/Ro ships, the maximum allowed vertical distance from the keel to the centre of gravity , *KG*, often determines the total cargo capacity.

The development of ship hulls with large beam to draft ratios, *B/T*, has made it possible to use larger *KG* values then can be used in ships with conventional main dimensions. New hull forms such as single skeg, twin skeg or open stern types, have been developed to decrease resistance or increase propulsive efficiency for these types of hulls. The modern hull forms have increased water plane area coefficient, C_{WA}, in the still water design condition and therefore allow for still larger *KG* values in comparison with traditional hull forms at the same main dimensions.

In a wave train, however, the water plane area might be dramatically changed and the actual transverse restoring moment during a certain time interval can become insufficient. The irregular character of sea waves usually makes this effect less serious, but a significant loss of stability even during such short time as half a minute can be dangerous, if combined with a strong sheer or sudden green water on deck from breaking waves.

The actual course of a capsize must be studied in model tests or in a time step simulation taking into account all the hydrostatic and hydrodynamic forces as well as inertia forces from ship motions. The risk of beeing captured in a hazardous situation is however very much dependent on the initial stability of the ship in waves, and this can be analysed qualitatively with less sofisticated methods.

A cyclic change of the transverse restoring moment can furthermore result in a parametric excitation of roll motion. Although the static stability is satisfactory, unacceptable roll might develope if the restoring moment changes in resonance with the natural roll frequency. If the roll damping is low, the amplitudes might increase so rapidly that it could lead to shift of cargo and a capsize in just a few cycles.

In this paper initial stability characteristics are compared in waves for different hull forms, with a *B/T* of 4.5, and with a block coefficient C_B of 0.65. The study is performed with a quasi static approach, taking into account regular wave profiles and ship motions calculated with strip theory.

2 HULL FORMS

Four different hull forms have been chosen for the comparative study.

A, B and C represent modern hull forms with bulbous forebody and pronounced flare. A has a conventional afterbody, B an open stern, and C a twin skeg design. B and C have full deck width at the transom stern. D is a traditional U-shaped hull form with a relatively small water plane area and very little flare.

Hull A is a tank test model (SSPA 2062-A) that have been streched and scaled to the main dimensions used in this study. Hull B and C are tank test models (SSPA 2269-B and 2270-A) at their actual dimensions while hull D is a streched and scaled Series 60 model.

Main dimensions for the different hull forms are:

$$L_{PP} = 212.3 \ m$$
$$B = 32.2 \ m$$
$$T = 7.16 \ m$$
$$D = 18.68 \ m$$
$$C_B = 0.65$$

In fig.2.1 are presented scetches of sectional forms and individual hydrostatic particulars for the studied hulls. There is a significant difference in the vertical position of the metacentrum, ***KM***, between D and the modern hull forms A,B,C. This difference is maintained, as shown in fig.2.2, for different draughts and trim around the design condition.

Table 2.1 shows the maximum allowed ***KG***, and the minimum initial metacentric height ***GM***, according to different intact stability criteria. Criteria 1-4 are applied by IMO ,while the additional criterion 5, related to the stability width, is applied by the National Swedish Administration for Shipping and Navigation. Criterion 5 is primarily determined by the deck height and therefore not considered as relevant as criteria 1-4, for the purpose of comparing influence from different hull forms. It is however, the limiting criterion for the studied hulls.

In fig.2.3 are compared restoring lever $GZ(\phi)$ based on a maximum ***KG*** according to the IMO-criteria and on criterion 5. The different applied criteria result in very different stability characteristics for the hull forms. Criterion 3, limiting among the IMO-criteria for the modern hull forms A, B and C, is extraordinary favourable for the twin skeg hull. Hull B is allowed to travel with a vertical centre of gravity more then one metre higher then the others

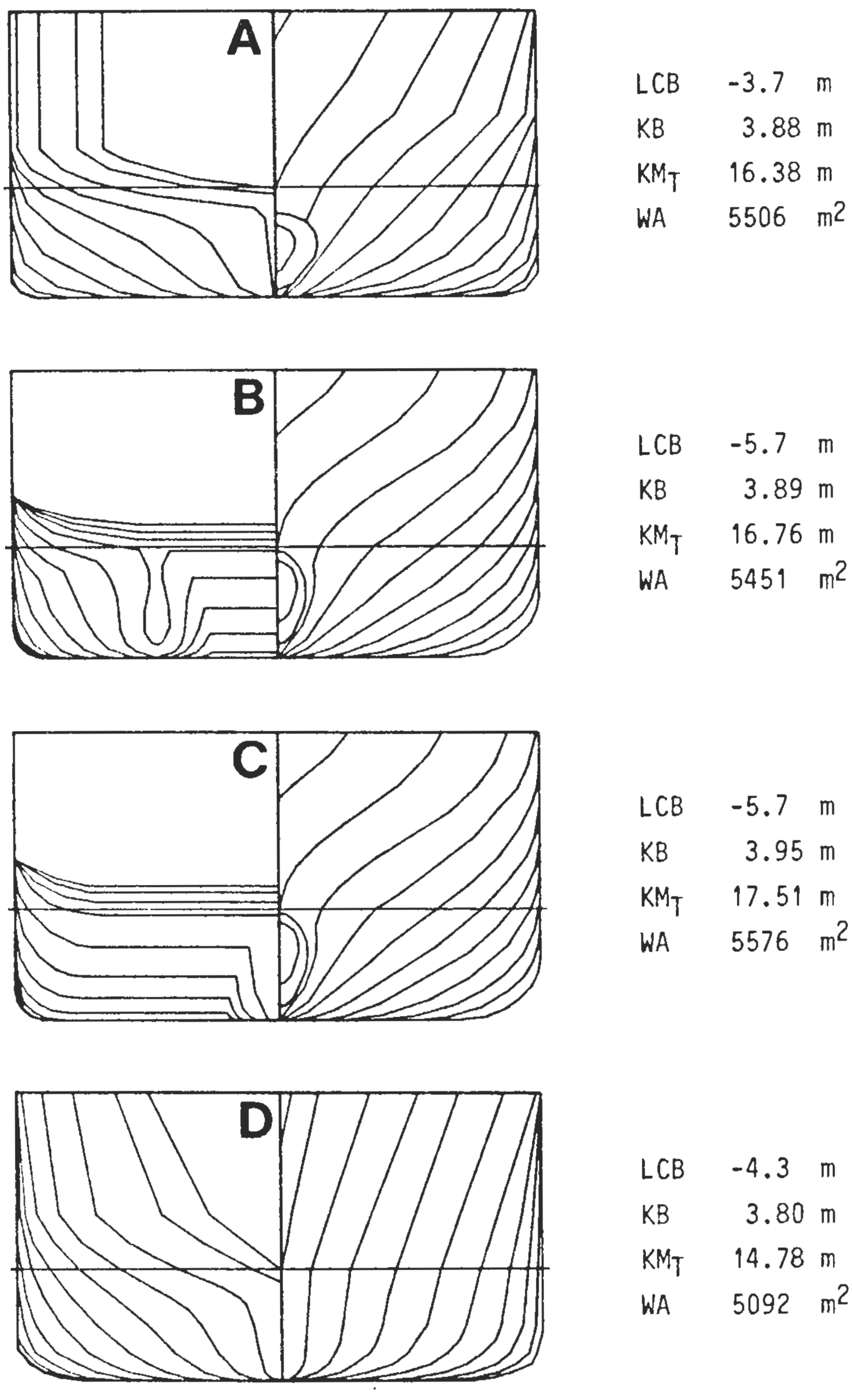


Fig.2.1 Studied hull forms

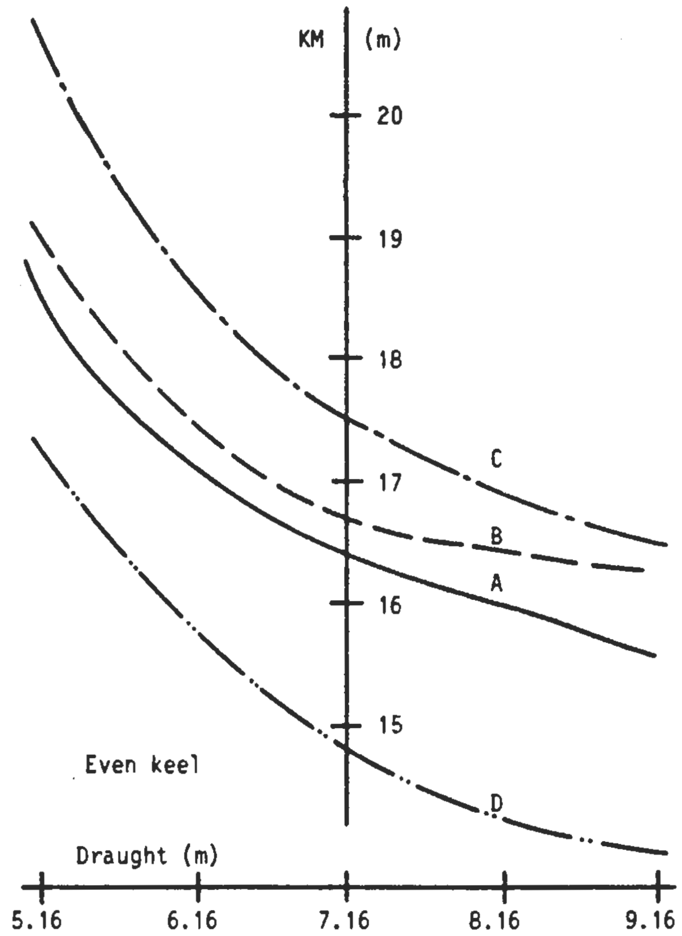


Fig.2.2a *KM* variation by draught

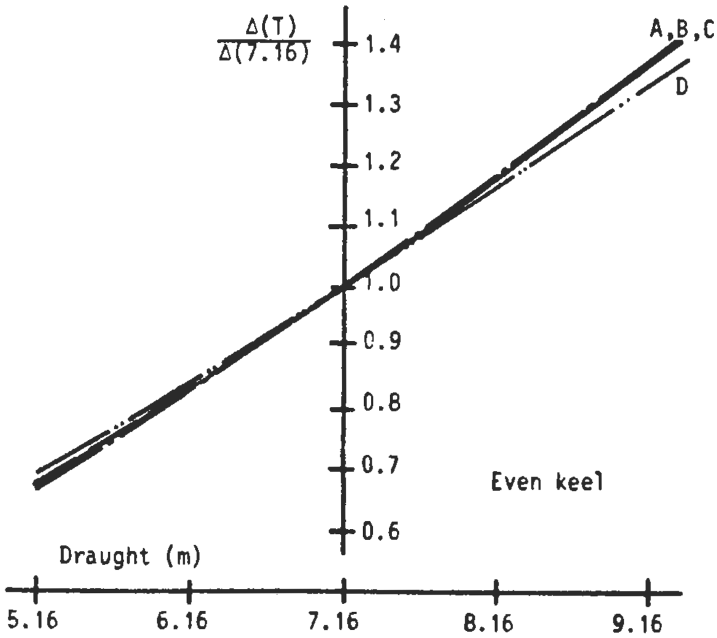


Fig.2.2b Relative variation of displacement *Δ* by draught

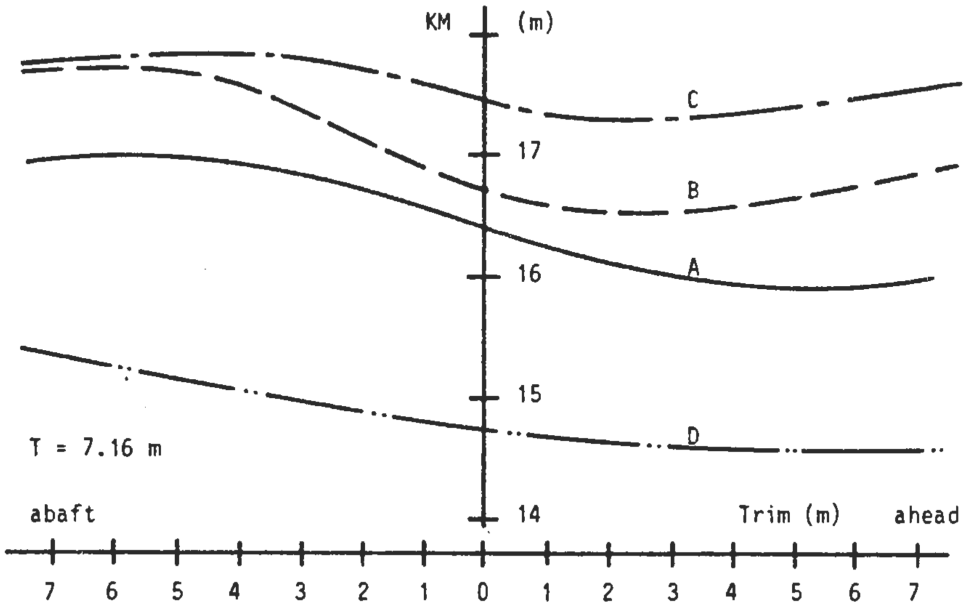


Fig.2.2c **KM** variation by trim

Intact Stability Criteria:	Maximum KG: A	B	C	D
1 $\int_0^{30} GZ d\phi > 0.055$ mrad	16.36	16.99	17.48	14.90
$\int_0^{40} GZ d\phi > 0.090$ mrad	16.28	16.99	17.28	14.97
$\int_{30}^{40} GZ d\phi > 0.030$ mrad	16.23	17.04	17.06	15.13
2 $GZ_{max}(\phi>30) > 0.2$ m	16.40	17.20	17.37	15.12
3 $\phi(GZ_{max}) > 30$ deg	15.42	16.58	15.50	15.24
4 $GM_0 > 0.15$ m	16.24	16.60	17.35	14.63
5 $GZ(\phi<60) > 0.0$	14.29	14.64	14.75	13.56

Minimum GM acc. to Crit 1-4	0.96	0.18	2.01	0.15
Minimum GM acc. to Crit 5	2.09	2.12	2.76	1.22

Table 2.1 **Maximum allowed *KG* and minimum *GM* according to different intact stability criteria**

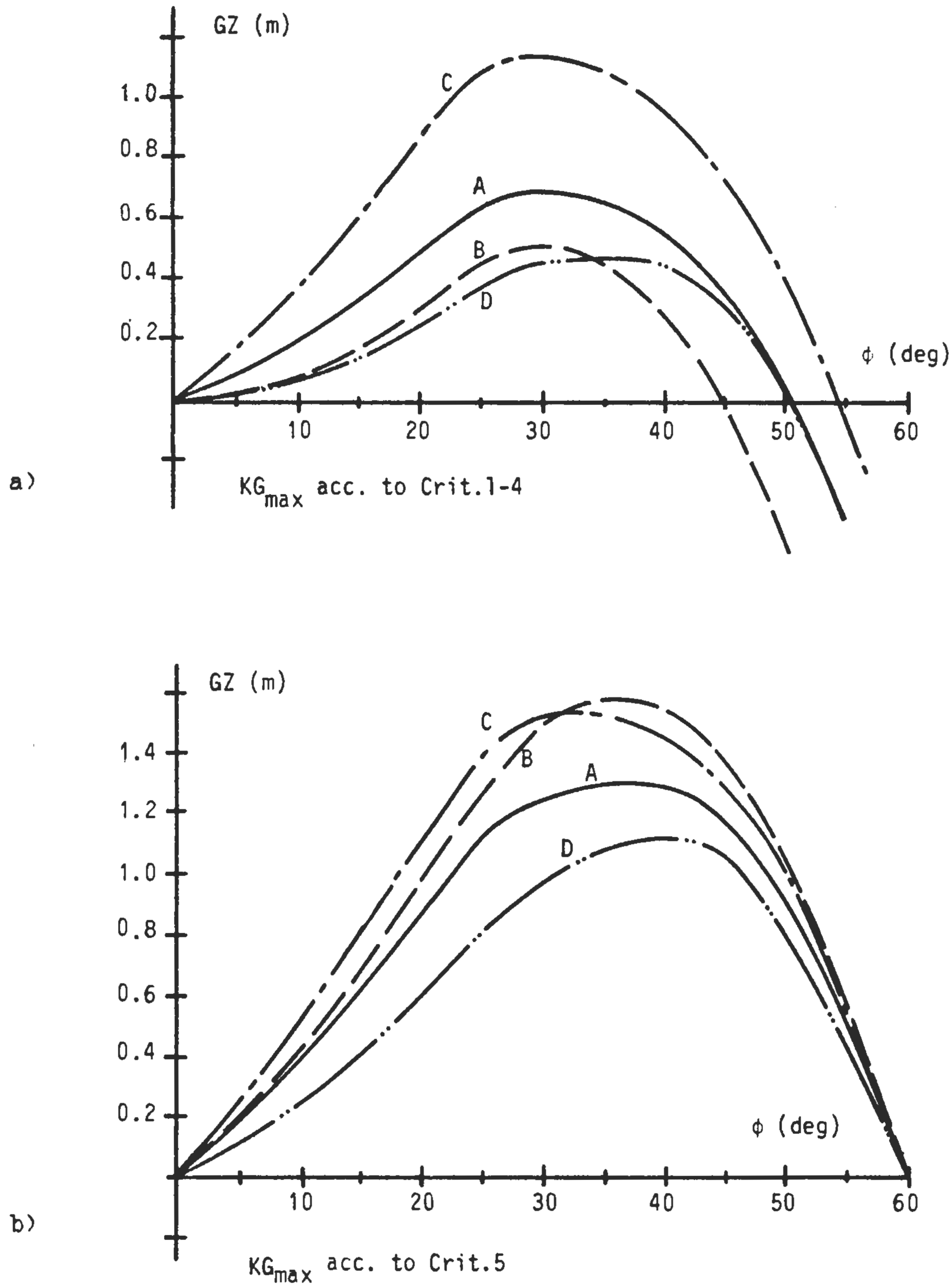


Fig.2.3 *GZ*-curves evaluated at:
a) maximum *KG* according to IMO-criteria 1-4
b) maximum *KG* according to criterion 5

3 LOSS OF STABILITY IN WAVES WITH CLOSE TO ZERO ENCOUNTERING FREQUENCIES

Loss of stability in waves is to be considered as critical only when it lasts for enough long time. This implies that the quality of different hull forms in this respect should be compared in gravity waves with low encountering frequencies. In such waves, a quasi static approach of equilibrium between ship gravity forces and displacement forces can be justified, and ordinary hydrostatic calculations incorporating iteration for free trim and heave in waves can be used.

The relation between wave frequency ω_w, encountering frequency ω_e, relative wave direction β, and ship speed V, for ships in regular gravity waves can be written:

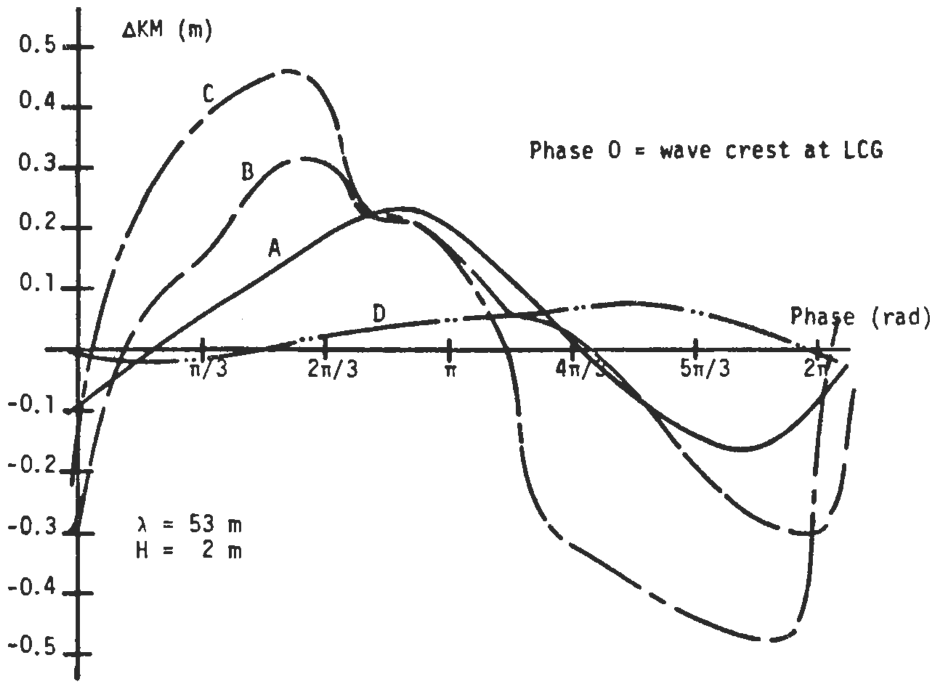
$$\omega_e = \omega_w - V \frac{\omega_w^2}{g} \cos\beta \tag{3.1}$$

Using Froudes number $F_{nL} = V/\sqrt{(gL)}$ and $\omega_w = \sqrt{(2\pi g/\lambda)}$,
the following equation is obtained for critical regular wave lengthes with $\omega_e = 0$:

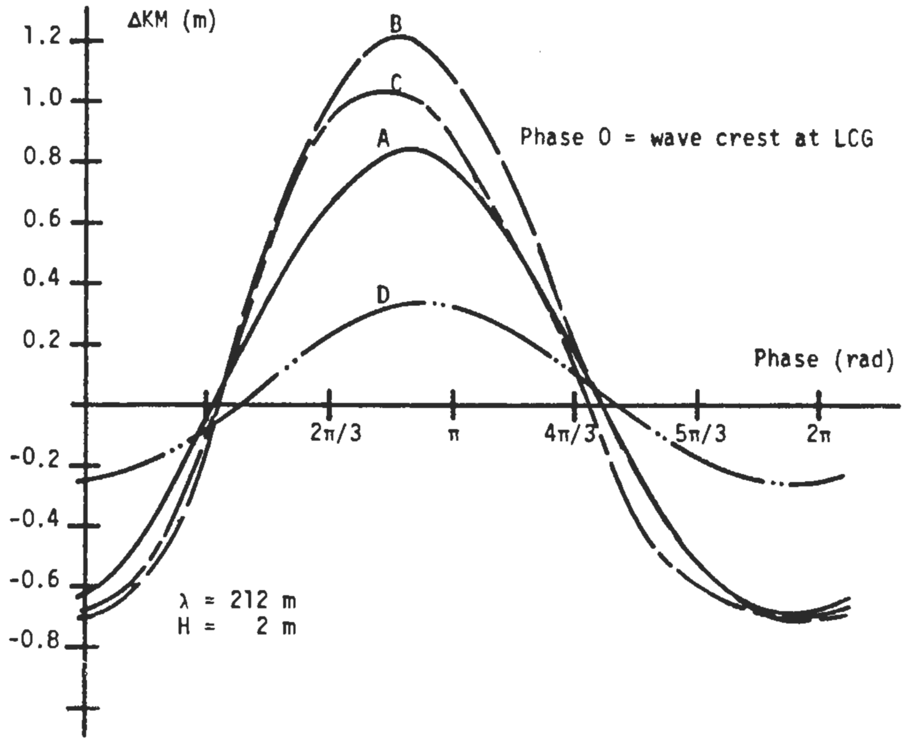
$$\lambda_{crit} = 2\pi L_{pp}(F_{nL}\cos\beta)^2 \tag{3.2}$$

The studied ships have a service speed of about 18 kn, $F_{nL} = 0.2$, and the largest critical wave length with zero encountering frequency becomes $L_{PP}/4 = 53$ m at a wave heading of $\beta = 0$ (following waves).

Fig.3.1a shows the variation of KM at different relative positions of the hulls in a regular wave with a height H of 2 m (double amplitude) and a length λ of 53 m. Fig.3.1b shows for comparison variation of KM for a wave length of 212 m. The hulls are free to trim and heave so that constant displacement and centre of boyancy is maintained. Fig.3.2 shows the maximum and minimum KM values as functions of the wave height in following regular waves with length 53 m.



a)



b)

Fig.3.1 Variation of KM at different longitudinal positions of the wave crest relative to the ships centre of gravity. Free trim and heave.
a) λ = 53 m b) λ = 212 m.

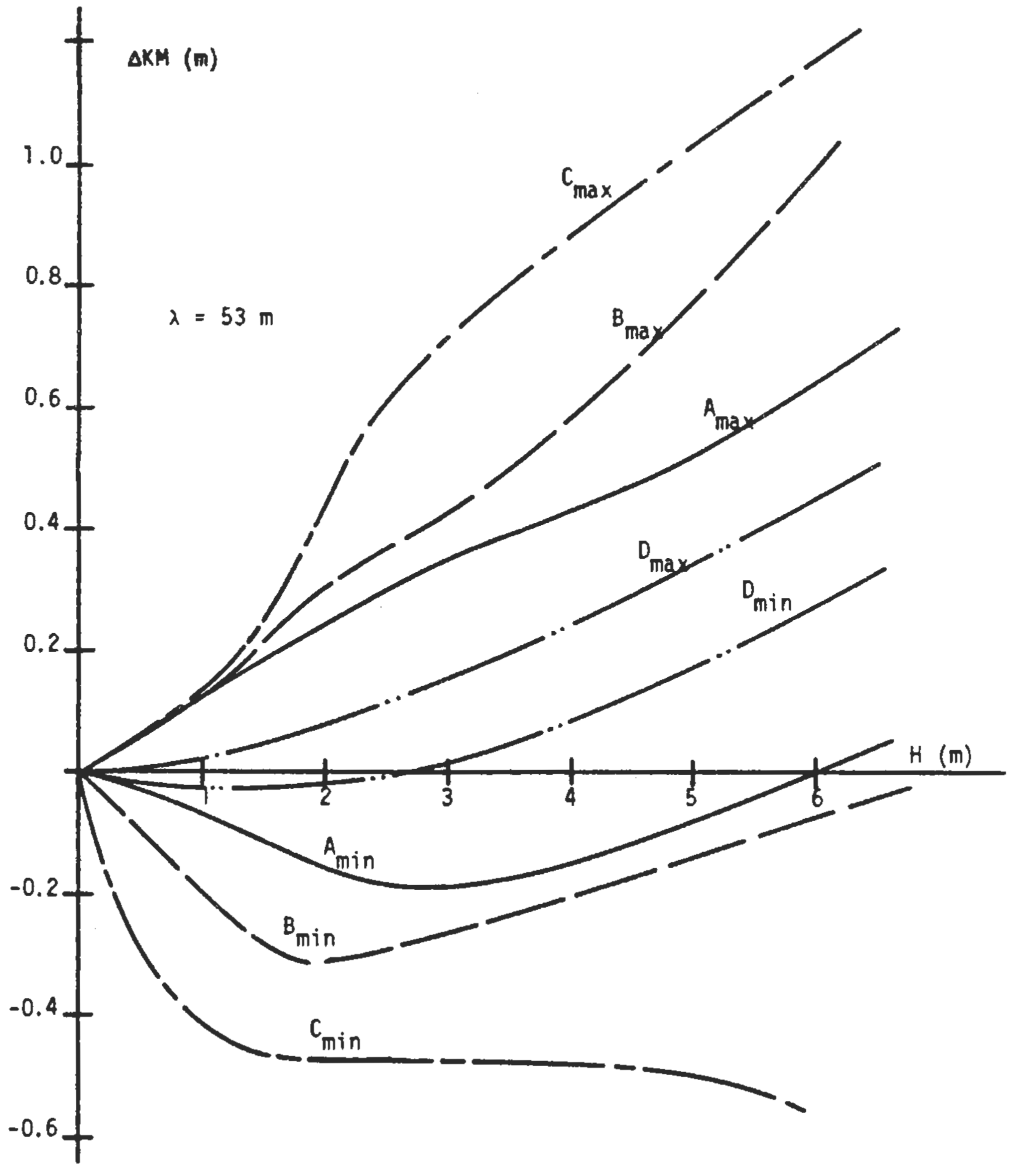


Fig.3.2 Maximum and minimum KM as function of the wave height. Free trim and heave. λ = 53 m.

The smallest KM values appear for wave heights of about 2 m, fig.3.2. There is a significant difference in the magnitude of the variation between the modern hull forms and the hull form D based on Serie 60. With maximum KG according to the IMO-criteria, the twin skeg hull B might loose all its initial stability in a wave height as low as 1 m.

In the case of zero encountering frequency, the *GZ*-curve can be calculated for ships with the same quasi static approach of free trim and constant displacement and centre of boyancy, as for the calculation of ***KM*** values in upright condition.
Fig 3.3 shows the *GZ*-curves for hull form B in calm water and in regular waves.

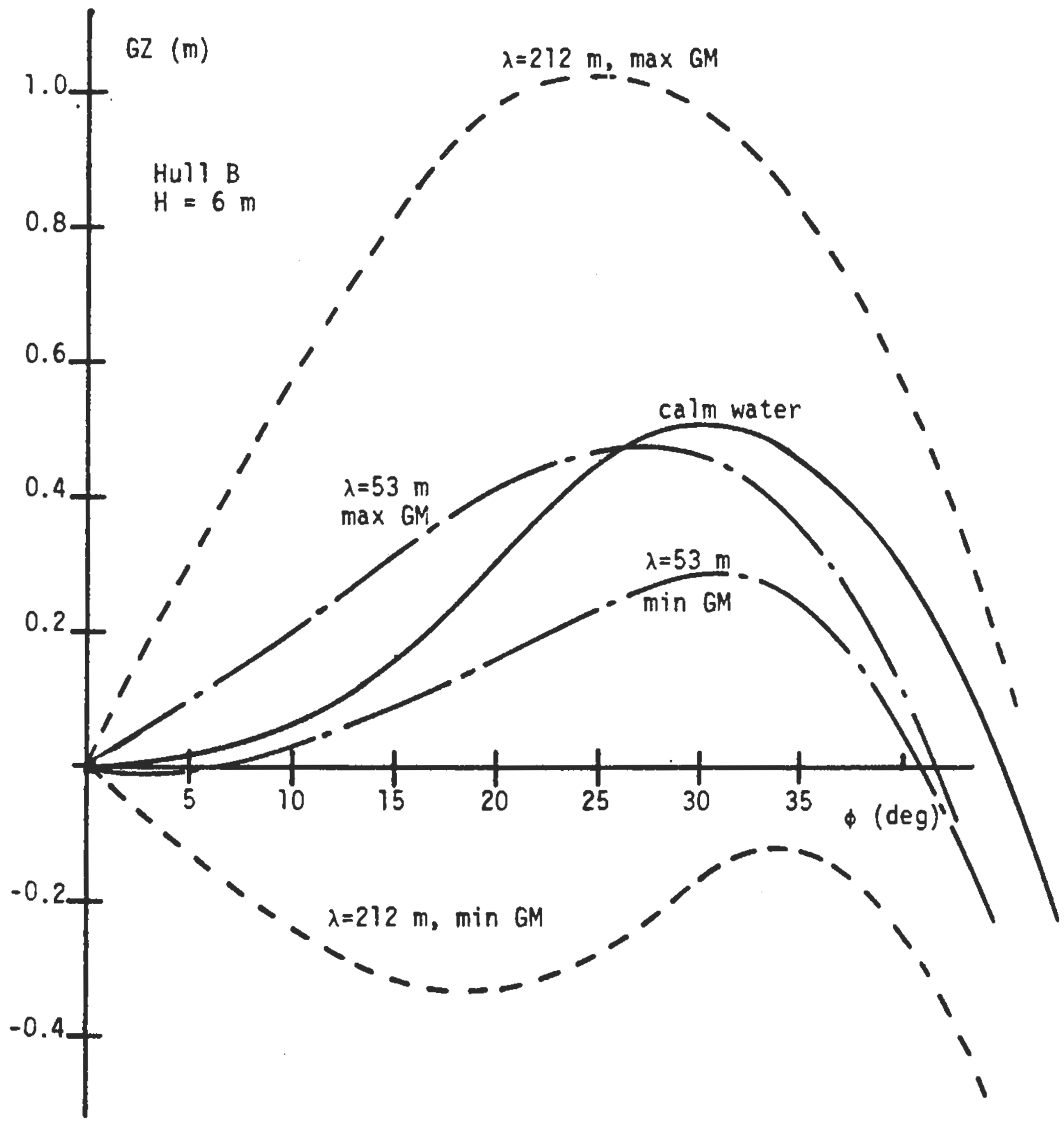


Fig.3.3 *GZ*-curves in regular waves. The wave crest at the position of maximum and minimum ***GM***$_o$.

In regular waves with length equal to the ship length, the magnitude of the ***KM*** variation is much larger than in the 53 m wave. It is a well known fact that small ships travelling with a high Froude number, close to 0.4 as for gravity waves at infinite depth, could be exposed to severe loss of stability in following waves. The results from this study shows that also the hull form is of large importance.

4 PARAMETRIC EXCITATION OF ROLL

When the variation in restoring moment due to ships motions and wave profile is periodically changed in resonance with the ships free rolling frequency, a heavy roll can develope even without external moments or an insufficient initial transverse stability.

Neglecting coupling terms from sway and yaw, the general homogenous equation of roll, $\phi(t)$, can be written:

$$(I+I_{add})\ddot{\phi} + B(\dot{\phi}) + g\Delta GZ(\phi) = 0 \tag{4.1}$$

$I+I_{add}$	is the mass moment of inertia including added mass moment
$B(\dot{\phi})$	is a general damping term
$g\Delta GZ(\phi)$	is the restoring term

For small amplitudes of roll, the damping function can be considered as linear viscous damping, $B(\dot{\phi})=b\dot{\phi}$, and the restoring lever $GZ(\phi)$ can be replaced by $GM\phi$. The homogenous equation of roll can then be written:

$$\ddot{\phi} + \frac{b}{(I+I_{add})}\dot{\phi} + \frac{g\Delta GM}{(I+I_{add})}\phi = 0 \tag{4.2}$$

or

$$\ddot{\phi} + 2\rho\omega_0\dot{\phi} + \omega_0^2\phi = 0 \tag{4.3}$$

with

$$\omega_0 = \sqrt{\frac{g\Delta GM}{I+I_{add}}} \tag{4.4}$$

$$\rho = \frac{b\omega_0}{2g\Delta GM} \tag{4.5}$$

ω_0 is the natural frequency of roll and ρ is a linear damping coefficient.

The variation of restoring moment in waves can be described by a periodic function,

$$h(t) = \frac{\Delta(t)GM(t)}{\Delta_0 GM_0} - 1 \qquad (4.6)$$

where $\Delta_0 GM_0$ is the restoring moment in calm water.

Including parametric excitation from the restoring moment term, eq. *(4.3)* is extended to:

$$\ddot{\phi} + 2p\omega_0\dot{\phi} + \omega_0^2(1+h(t))\phi = 0 \qquad (4.7)$$

The solution of eq. *(4.7)* might be stable or unstable depending on the amplitude and frequency of the ***h(t)*** function and on the magnitude of the damping.

Using numerical time simulation, the border of instability can be determined and presented in a stability chart as shown in fig.4.1. The figure has been prepared using a simulation method presented in [1], based on Pade approximant technique, sutible for solving problems with instabilities. The variation of restoring moment is in this figure assumed to be harmonic and independent on the actual angle of roll, $h(t) = h\cos(\omega_e t)$. Fig.4.2 shows some examples of time series used as base for the stability chart.

The most important unstable region is considered to be when the wave frequency of encounter is twice the natural frequency of roll. At very low ω_e, unstable conditions are naturally found when ***h*** is larger then 1.0, i.e when ***GM*** is negative.

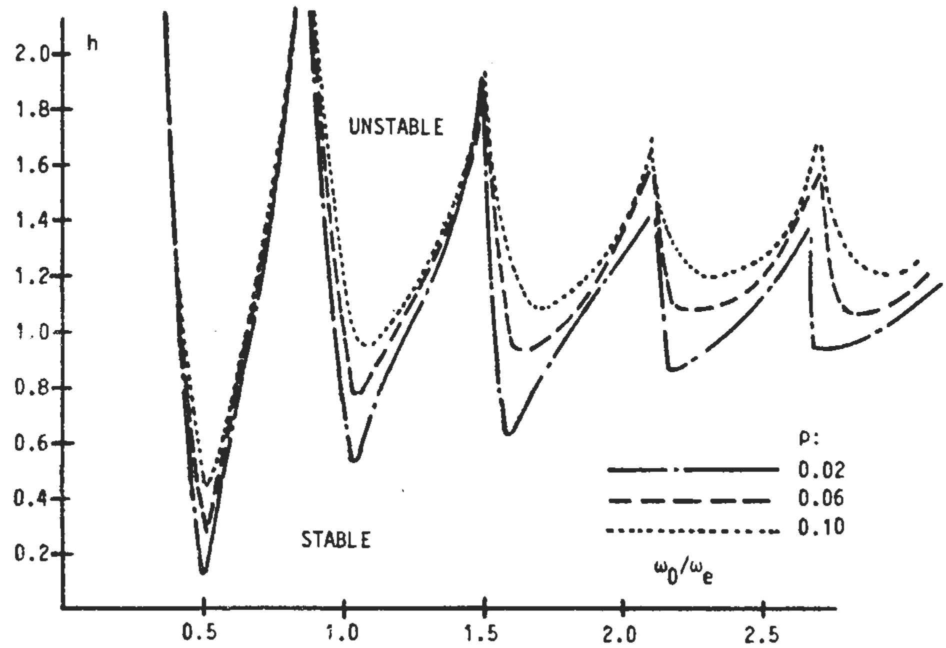


Fig.4.1 Borders of instability in the solution if eq. *(4.7)*.

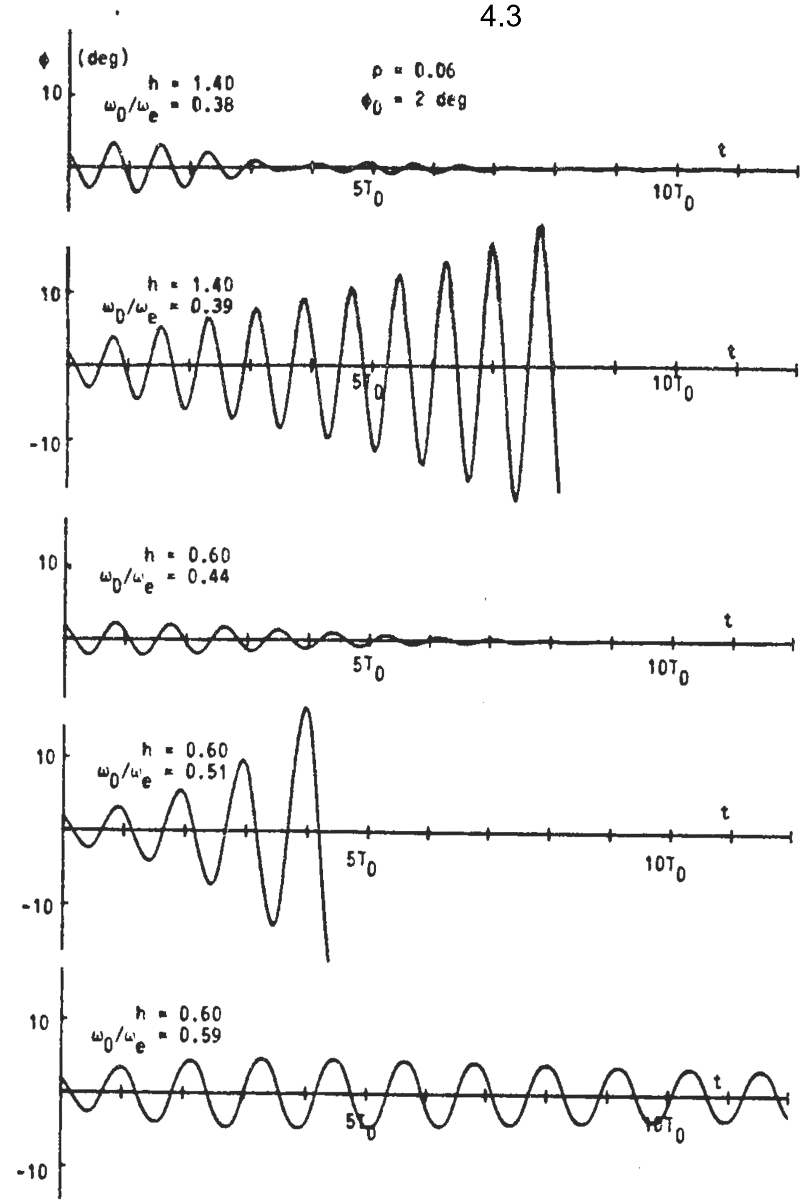


Fig.4.2 Example of time series solutions of eq. *(4.7)*.

The variation of the restoring term is due to the ships vertical motions in combination with the wandering position of the wave profile along the ship. Since ships vertical motions, heave and pitch, are known to be accurately calculated by ordinary strip theory, the time variation of restoring moment can be evaluated by taking draught and trim in a time step procedure from strip theory calculated motions, and combine them with the actual wave profile in the hydrostatic calculation. Such calculations have been performed with the HYSS program, [2], for a number of regular wave frequencies of different headings.

At each regular wave, the time variation of $h(t)$ have been evaluated for a *GM* giving a natural frequency of roll corresponding to half the encountering frequency. The function $h(t)$ is for small wave heights well represented by a linear harmonic function while in higher waves the periodic function is distorted with the mean value significantly different from zero. The root mean square of the deviation from the mean value of $h(t)$, $rms(h)$, is however found to be close to a linear function of the wave height, see fig.4.4. This value is here used as a quality parameter for the comparison of different hull forms.

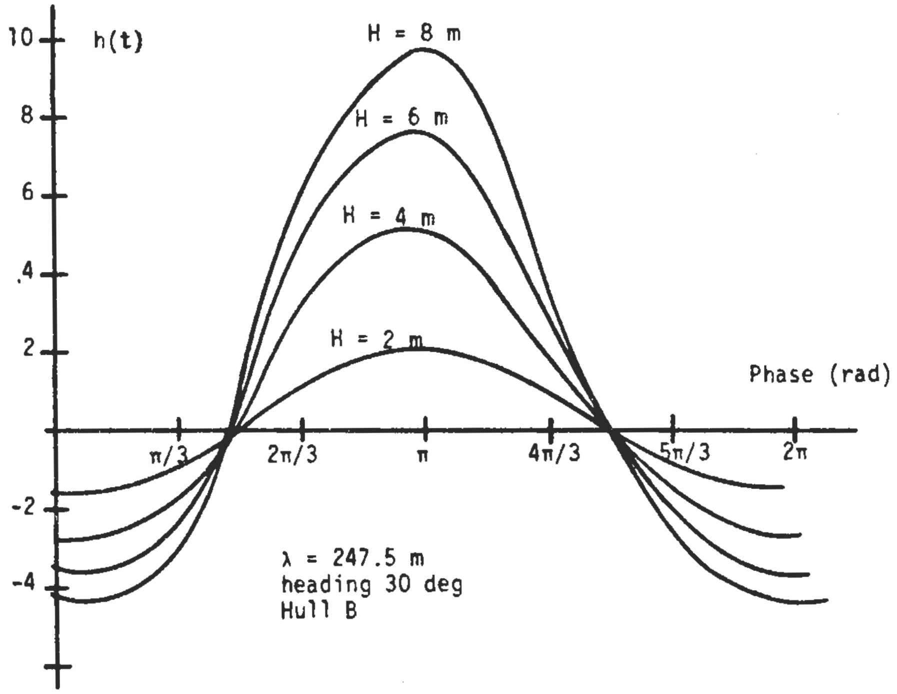


Fig.4.3 Example of *h(t)* for different wave heights, hull form B.

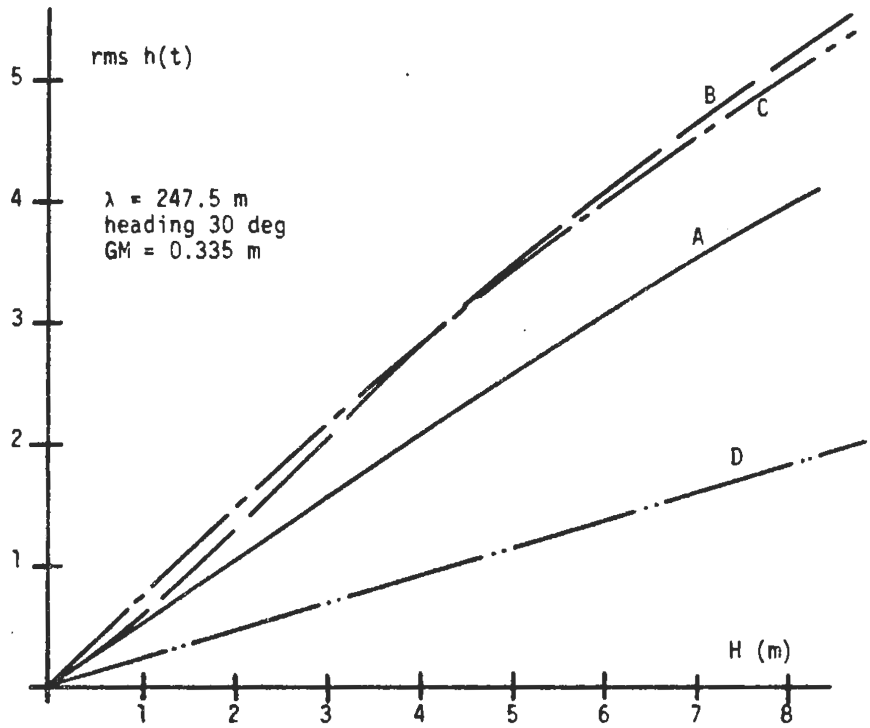


Fig.4.4 *rms(h)* as function of the wave height.

In Tables 4.1a-g and in figs.4.5a-c is presented *rms(h)* at a wave height of 2 m, as function of the encountering frequency for different wave headings. The figures show clearly the different characteristics of the modern hull forms A,B and C in comparison with the traditional hull form D. According to eq. *(4.6)*, $h(t)$ is highly dependent on the GM_0 value. The largest risk of parametric excitation is therefore found in following waves where the resonance frequency of roll corresponds to small GM values.

Wave heading: 0 deg H = 2m

a)

wave			condition		rms h(t)			
ω	λ	ω_e	$GM^{\frac{1}{2}}$	GM	A	B	C	D
.3	685.0	.216	.420	.176	.531	.569	.561	.250
.4	385.0	.251	.488	.238	.988	1.204	1.313	.435
.5	247.5	.267	.519	.269	1.557	2.021	2.148	.657
.6	171.2	.264	.513	.263	1.984	2.621	2.548	.813
.7	125.8	.243	.472	.223	1.754	2.187	1.962	.822
.8	96.3	.203	.394	.156	1.307	1.351	2.179	.766
.9	76.1	.145	.282	.079	3.726	5.151	6.404	1.173
1.0	61.6	.067	.130	.017	-	-	-	-
1.1	50.9	-.028	.054	.003	-	-	-	-
1.2	42.8	-.143	.278	.077	1.046	1.685	3.783	.273
1.3	36.5	-.276	.536	.288	.125	.342	.857	.076
1.4	31.4	-.428	.832	.692	.075	.123	.294	.010
1.5	27.4	-.598	1.162	1.350	.027	.070	.144	.016
1.6	24.1	-.788	1.531	2.344	.027	.045	.077	.013

Wave heading: 30 deg H = 2m

b)

wave			condition		rms h(t)			
ω	λ	ω_e	$GM^{\frac{1}{2}}$	GM	A	B	C	D
.3	685.0	.227	.441	.195	.375	.402	.394	.180
.4	385.0	.271	.527	.277	.678	.714	.719	.303
.5	247.5	.298	.579	.335	1.046	1.310	1.479	.450
.6	171.2	.309	.600	.360	1.374	1.797	1.783	.563
.7	125.8	.304	.591	.349	1.376	1.762	1.611	.580
.8	96.3	.283	.550	.302	.923	1.024	.967	.513
.9	76.1	.246	.478	.228	1.021	1.300	1.902	.446
1.0	61.6	.192	.373	.139	1.995	2.645	3.058	.671
1.1	50.9	.123	.239	.057	-	-	-	-
1.2	42.8	.037	.072	.005	-	-	-	-
1.3	36.5	-.065	.126	.016	-	-	-	-
1.4	31.4	-.183	.356	.126	.219	.701	1.940	.152
1.5	27.4	-.317	.616	.379	.132	.232	.514	.015
1.6	24.1	-.468	.909	.827	.044	.102	.248	.018
1.7	21.3	-.634	1.232	1.517	.037	.059	.132	.015

Table 4.1 *rms(h)* evaluated at resonance condition, $\omega_0 = 0.5\omega_e$ H = 2 m, a) β = 0 deg, b) β = 30 deg.

c)

Wave heading: 60 deg H = 2m

wave			condition		rms h(t)			
ω	λ	ω_e	$GM^{\frac{1}{2}}$	GM	A	B	C	D
.3	685.0	.258	.501	.251	.111	.117	.114	.055
.4	385.0	.325	.631	.399	.191	.201	.190	.086
.5	247.5	.383	.744	.554	.281	.316	.291	.125
.6	171.2	.432	.839	.705	.380	.464	.533	.164
.7	125.8	.472	.917	.841	.464	.594	.656	.194
.8	96.3	.502	.975	.951	.506	.661	.666	.205
.9	76.1	.522	1.014	1.029	.471	.605	.591	.192
1.0	61.6	.534	1.038	1.077	.349	.433	.397	.163
1.1	50.9	.536	1.041	1.085	.192	.195	.215	.131
1.2	42.8	.528	1.026	1.052	.210	.274	.406	.090
1.3	36.5	.512	.995	.990	.301	.403	.476	.084
1.4	31.4	.486	.994	.892	.224	.225	.298	.114
1.5	27.4	.451	.876	.768	.174	.234	.435	.065
1.6	24.1	.406	.789	.622	.221	.312	.470	.059
1.7	21.3	.352	.684	.468	.183	.290	.574	.057
1.8	19.0	.289	.562	.315	.244	.368	.733	.076
1.9	17.1	.217	.422	.178	.226	.635	1.467	.098
2.0	15.4	.135	.262	.069	.518	.891	2.890	.161

d)

Wave heading: 90 deg H = 2m

wave			condition		rms h(t)			
ω	λ	ω_e	$GM^{\frac{1}{2}}$	GM	A	B	C	D
.3	685.0	.300	.583	.340	.201	.017	.033	.025
.4	385.0	.400	.777	.604	.025	.019	.046	.034
.5	247.5	.500	.972	.944	.026	.020	.060	.041
.6	171.2	.600	1.166	1.359	.025	.021	.071	.046
.7	125.8	.700	1.360	1.850	.029	.034	.062	.046

e)

Wave heading: 120 deg H = 2m

wave			condition		rms h(t)			
ω	λ	ω_e	$GM^{\frac{1}{2}}$	GM	A	B	C	D
.3	685.0	.342	.665	.442	.030	.043	.060	.033
.4	385.0	.475	.923	.852	.034	.056	.064	.029
.5	247.5	.617	1.199	1.437	.033	.070	.081	.036
.6	171.2	.768	1.492	2.227	.014	.052	.070	.070

Table 4.1 *rms(h)* evaluated at resonance condition, $\omega_o = 0.5\omega_e$
H = 2 m c) β = 60 deg, d) β = 90 deg, e) β = 120 deg

f)

Wave heading: 150 deg H = 2m

wave			condition		rms h(t)			
ω	λ	ω_e	$GM^{1/2}$	GM	A	B	C	D
.3	685.0	.373	.725	.525	.079	.101	.094	.022
.4	385.0	.529	1.028	1.056	.101	.154	.168	.014
.5	247.5	.702	1.364	1.860	.093	.150	.172	.045

g)

Wave heading: 180 deg H = 2m

wave			condition		rms h(t)			
ω	λ	ω_e	$GM^{1/2}$	GM	A	B	C	D
.3	685.0	.384	.746	.557	.100	.129	.113	.016
.4	385.0	.549	1.067	1.138	.126	.186	.215	.020
.5	247.5	.733	1.424	2.028	.108	.170	.197	.044

Table 4.1 *rms(h)* evaluated at resonance condition, ω_o = 0.5ω_e, *H* = 2 m f) β = 150 deg, g) β = 180 deg.

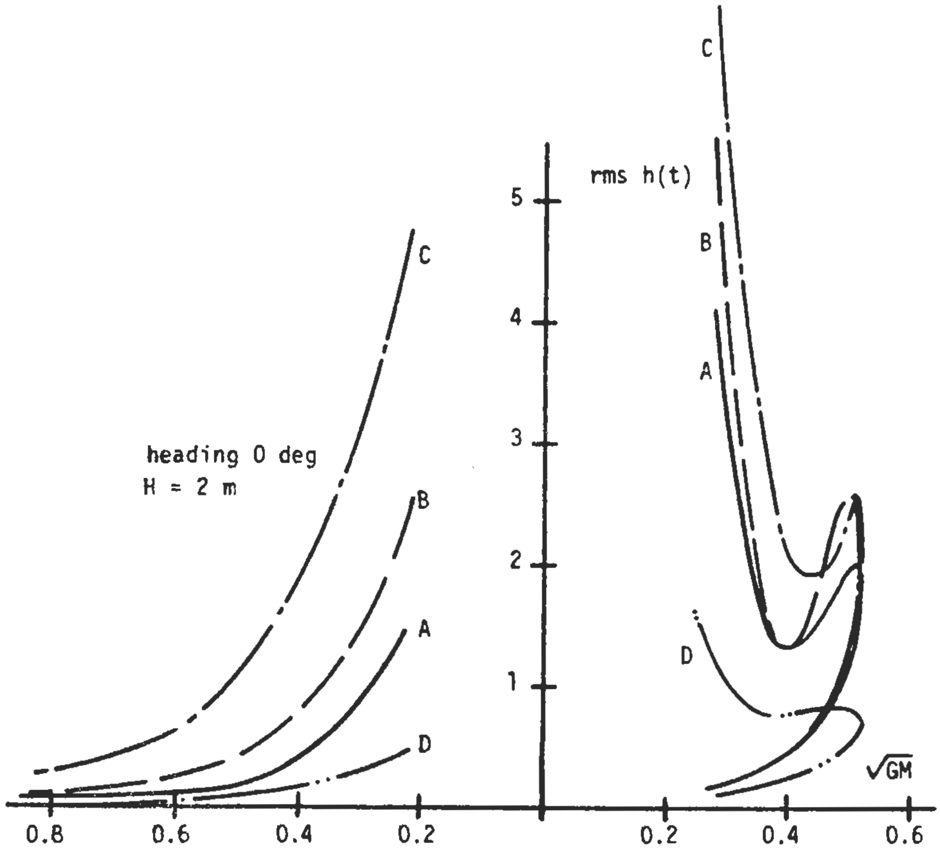


Fig.4.5 *rms(h)* evaluated at resonance condition, ω_o = 0.5ω_e, *H* = 2 m, a) β = 0 deg.

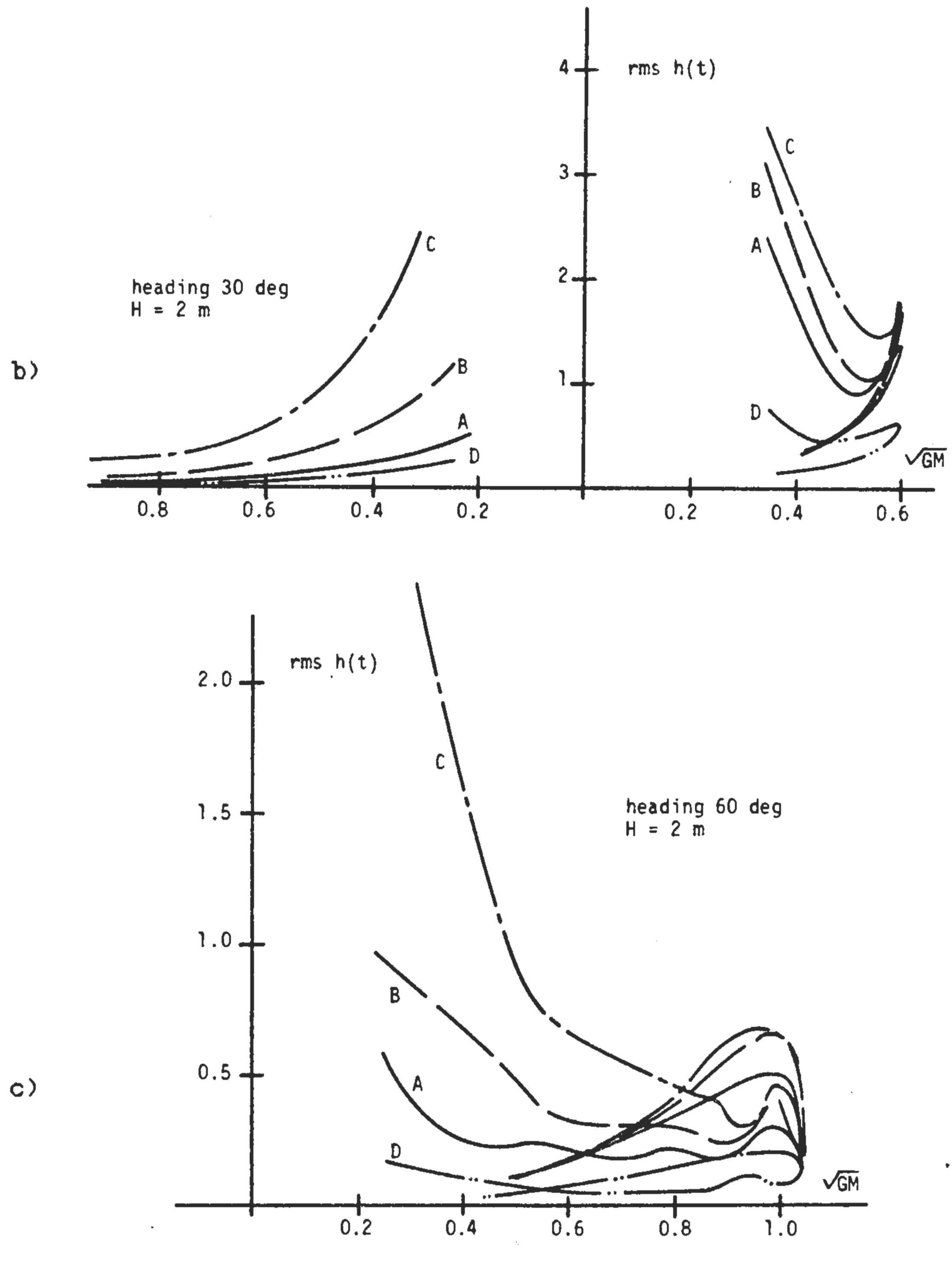


Fig.4.5 ***rms(h)*** evaluated at resonance condition, $\omega_0 = 0.5\omega_e$ H = 2 m, b) β = 30 deg c) β = 60 deg.

The judgement of which amplitude levels of the ***h(t)***-function that might be acceptable should be based on results from model tests and numerical simulations in regular waves as well as in irregular sea states. The quasi static approach for regular waves used in this study seems however to be efficient and useful for comparison of different hulls and could be used as base for criteria concerning stability in waves.

5 REFERENCE TO MODEL TEST

Parametric exitation of roll has been investigated at the SSPA Maritime Dynamics Laboratory in Gothenburg ,[3] and [4],for the original tank test model 2062-A corresponding to the following full scale dimensions:

$$L_{PP} = 180.0 \text{ m}$$
$$B = 27.3 \text{ m}$$
$$T = 9.1 \text{ m}$$
$$C_B = 0.65$$

This Ro/Ro ship model was considered not to be very sensitive to parametric excitation of roll, but the phenomena was still observed in large following waves. Fig.5.1 shows measured values of waves and ship motions in following regular waves with length 156 m and wave height 8 m. GM was 0.81 m and resonance was obtained at a reduced speed of 5.8 knots. The damping coefficient ρ was at this speed evaluated from decay test and shown to be 0.04 at a roll angle of about ±3 deg.

The $h(t)$ function at the actual observed unstable condition in the model test have been examined with the same quasi static approach as for the hull forms in this study. With heave and pitch amplitudes and phases evaluated approximately from test results, the $rms(h)$ was calculated to 0.99 with a mean value of 0.65. With motions from strip calculation the corresponding values becomes 1.02 and 0.63 respectively.

Although reference is made only to this single model test, it is obvious that $h(t)$ values as high as those found in Tables 4.1 are unacceptable.

In [3] is also presented some GZ-curves up to 35 deg angle of heel for the model in regular waves. Those calculations where made with a program developed at SSPA using a panel method for calculation of the integrated pressure resultant instead of the displacement. By using this method, also the Smith effect of pressure distribution under waves can be taken into account. This effect of decreasing pressure variations with the depth should have very little effect on the GZ-curve in waves with lengths several times the ship draught. When comparing results from the HYSS program and the SSPA program in a wave length of 156 m, no significant difference was found.

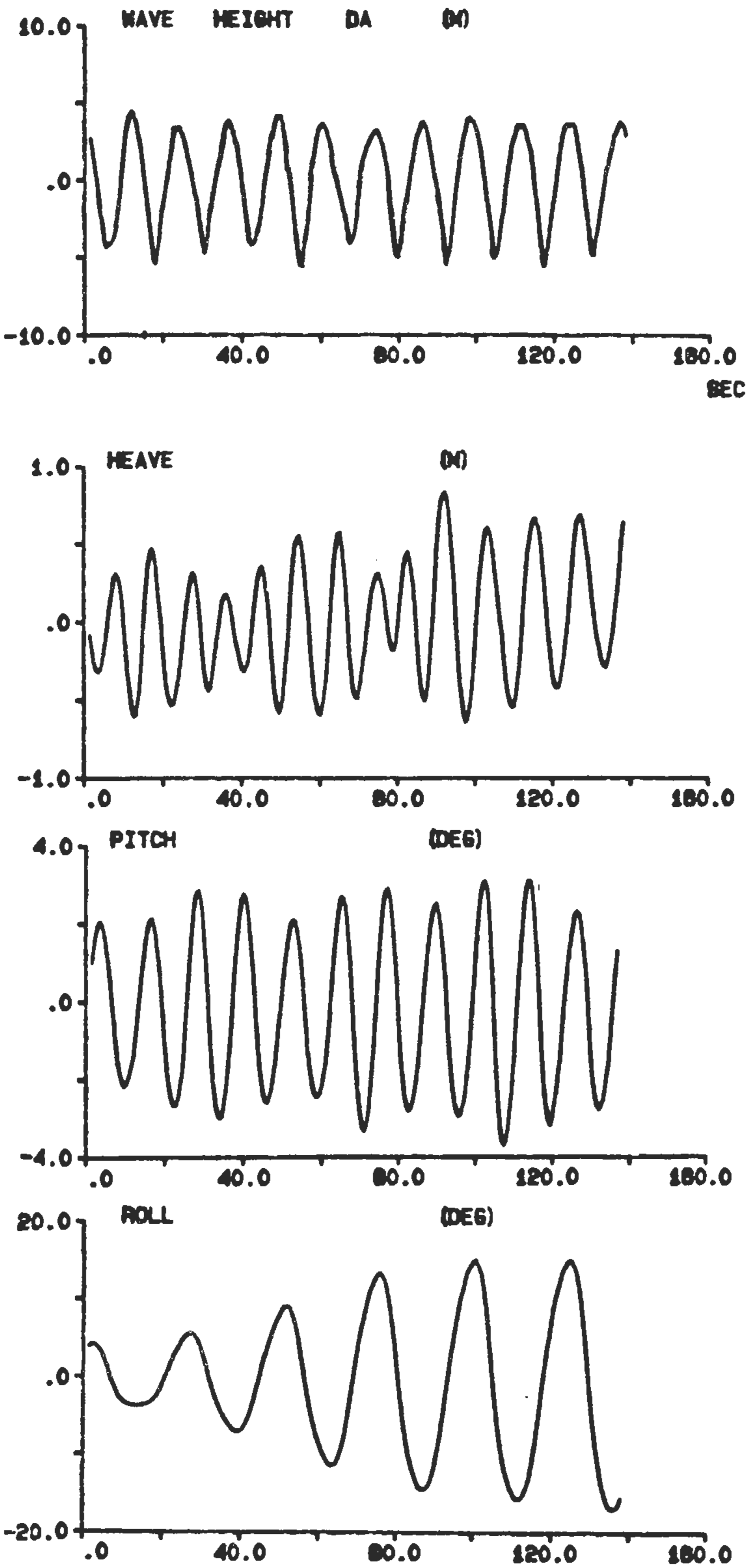


Fig.5.1 Results from model test of a Ro/Ro ship in following regular waves. Parametric excitation of roll observed at resonance $\omega_e = 2\omega_0$. From [4].

6 INFLUENCE OF B/T RATIO

The variation of transverse stability in waves is primarily a problem for ships with large *B/T* ratios. In this study, the different hull forms have a *B/T* of 4.5. To get a view of *B/T* influence the hulls have been scaled, with maintained length, displacement and block coefficient, to *B/T* 2.5, 3.5, and 5.5.

As shown in fig.6.1 and fig.6.2, ***KM*** is doubled when *B/T* is increased from 2.5 to 5.5. At the same time the variation in metacentric height becomes more then five times larger. The comparison is made in a wave with 53 m length and 2 m height at zero encountering frequency.

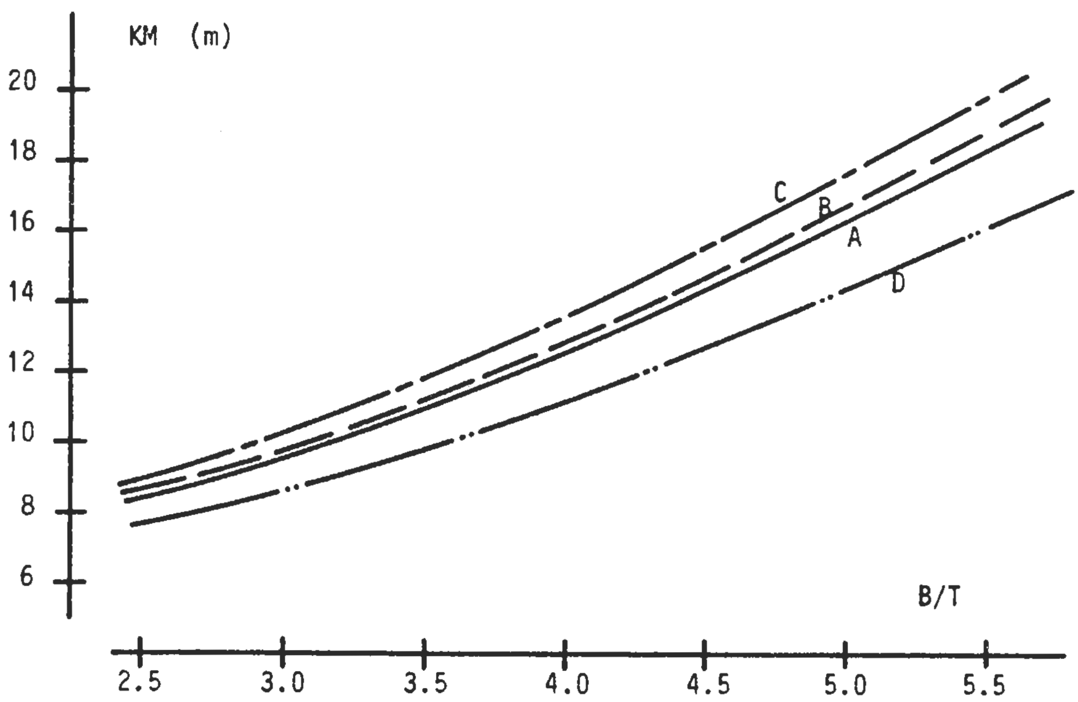


Fig.6.1 ***KM*** as function of *B/T*.

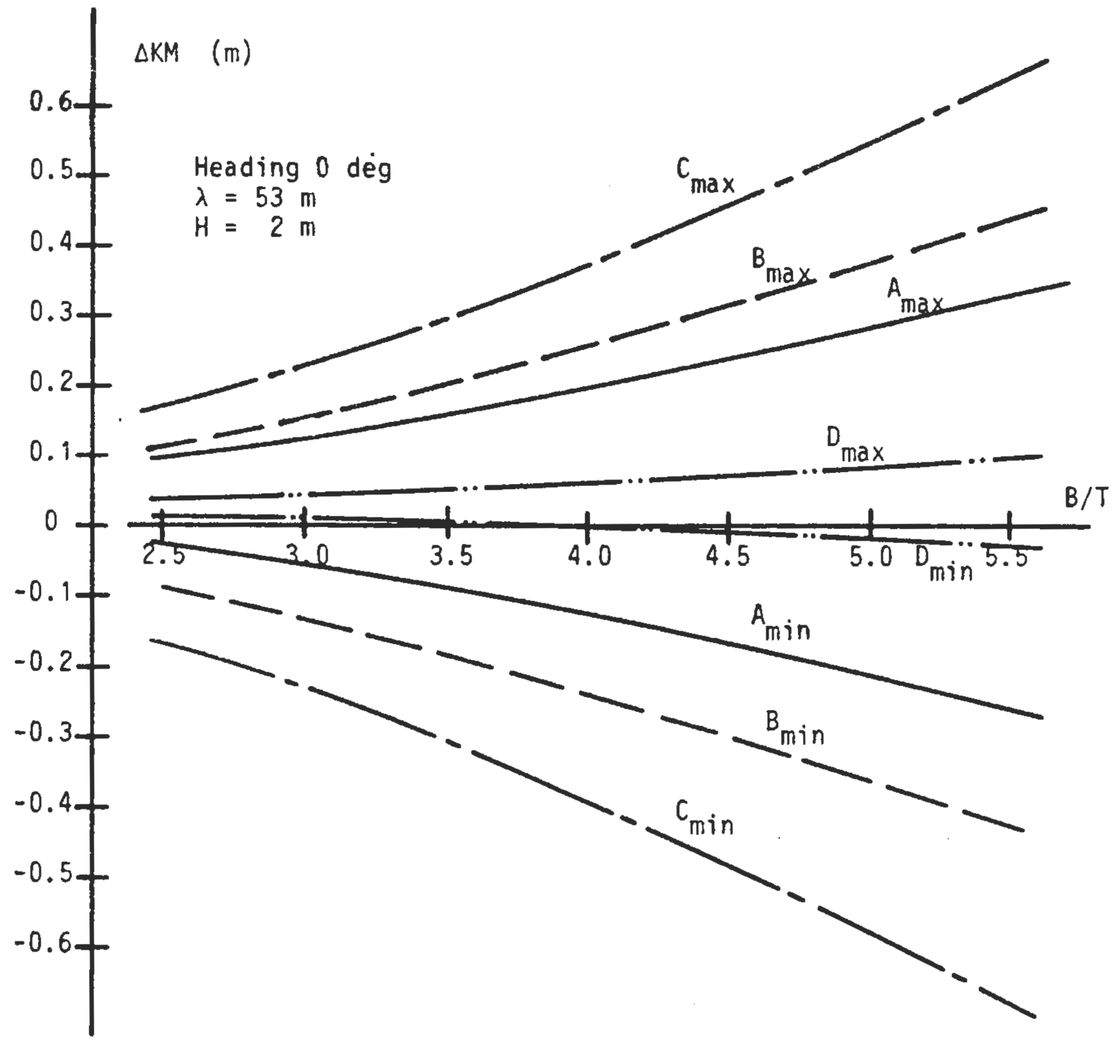


Fig.6.2 Amplidue of *KM* variation as function of *B/T*.
λ = 53 m, *H* = 2 m, β = 0 deg.

7 CONCLUSIONS

For ships with large beam to draft ratio, the initial transverse stability is found to vary significantly in regular waves. The stability variation is much larger for modern hull forms with wide transom sterns and pronounced flare at the fore body, than it is for more traditional sectional forms with vertical sides. This difference is to a major part due to the influence of the wave profile along the hull.

Existing stability criteria based on still water conditions does not properly account for different stability characteristcs in waves. There is evidently a potential danger that modern Ro/Ro ships are travelling with insufficient stability with respect to their performance in waves. The initial stability is for these ships of large importance because of their sensitivity to shift of cargo.

Insufficient initial stability can lead to temporary negative *GM* in following waves with the same speed as the ship or to parametric exitation of roll in waves encountering the ship with a frequency twice the natural frequency of roll. New criteria for stability in waves should preferable account for both these effects.

The comparative study presented here is performed with a quasi static time step procedure that takes into account regular wave profiles and linear ship motions. This method is suitable for integration in a standard intact stability calculation. Criteria, however, must be established based on calculations in irregular seas, with the parametric excitation of roll evaluated using numerical simulation. Such simulations should incorporate the influence of encountering frequency distribution and non linear damping as well as the variation of restoring moment.

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