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ON THE STABILITY CRITERIA FOR THE FISHING VESSELS

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ABSTRACT

The safety problem against ship's capsizing is still now of great importance particularly for small vessels. This is dramatically pointed out, as recorded in the last years, by the frequent casualties of fishing vessels and car ferries with following loss of human lives.

The present paper deals with a method for the quickly determination of the ship stability characteristics both in the preliminary design stage and in the operational stage of a fishing vessel.

The proposed method provides the possibility both of judging the effects on stability of several shape's parameters and also to determine the top vertical center of gravity position in any load ship's conditions according to the I.M.O. criterion.

The proposed methodology derives from the results obtained and explained in previous papers that deal with the determination of the geometrical parameters involved in the stability calculations related to the systematic series hulls.

INTRODUCTION

The evaluation of the transverse stability influences dramatically the choice of the main dimensions of a hull, particularly in the case of fishing vessels which, due to their form and size suffer very often from insufficient stability.

Therefore stability calculations should be carried out during the preliminary design; but in order to achieve a suitable accuracy, they require the knowledge of the table of offsets, which generally is produced in a further stage of the project.

The optimizing CAD techniques, which are nowadays used to design fishing vessels, call for quick procedures to verify stability, having as input only the main dimensions of the hull; the traditional approach based on the knowledge of the table of offsets cannot be used because it is too much time expensive.

If the hull is derived from a standard series the table of offsets and the resistance data are known, but even in this case the stability characteristics of the hull are very often not available.

On the base of the above considerations a research program has been planned and performed at the Department of Naval Engineering of Naples, the main objectives of which were:

- furnishing the fishing vessels designer with analytical relationships to quickly evaluate the stability;
- optimizing the hull dimensions and form, by analysing the dependence of the hull stability, defined according to I.M.O. criteria, on the main hull dimensions;
- furnishing the fishing vessel Master with a simple tool to evaluate the COG maximum vertical position related to I.M.O. criteria on the intact stability.

In particular the above analysis has been carried out on the hulls derived from the well-known Ridgely-Nevitt series of fishing vessels.

The following main results were already reported in published papers:

- a set of equations which gives analytically the offsets of a Ridgely-Nevitt hull (4)
- a set of equations which gives the I.M.O. indices of stability at any condition of loading (9)
- a stability analysis of the whole series, that is a sistematic calculation of stability indices carried out covering all the parameter ranges investigated by the series, which highlights the influence of stability on the choice of main hull dimensions (8).

The above results have been obtained using the theory of hull similarity and the regression analysis technique.

On the base of these theories, in the present paper a even more quick and simple analytical tool to judge the hull stability is reported, as two equations which give the maximum center of gravity height which fulfils all the I.M.O. stability criteria as a function of the main dimensions of the hull.

HULL SIMILITUDE THEORY AND STABILITY INDICES

Two hulls are defined similar if the co-ordinates X', Y', Z' of a generic point P' of the first hull are obtained from the co-ordinates X, Y, Z of a corresponding point P of the second one by a linear change, i.e. (fig.1):

$X' = l\,X \quad Y' = b\,Y \quad Z' = d\,Z$

here l, b, d are positive constants called imilitude ratios.

In such a transformation the on-dimensional form coefficients, like C_B, C_p nd so on, do not change; moreover, the uoyancy center co-ordinates X_B, Y_B, Z_B can be xpressed in the form:

$$X_B/L = X_B/L\,(C_V, C_\phi)$$

$$2Y_B/B = 2Y_B/B\,(C_V, C_\phi)$$

$$Z_B/T = Z_B/T\,(C_V, C_\phi)$$

where the non-dimensional quantities C_V, C_ϕ are defined as:

$$C_V = V/V_o \qquad C_\phi = (B/T)\tan\phi\ ,$$

- V is the actual displacement volume,
- V_o is the design displacement volume
- L, B, T are the length between perpendiculars, the design beam and draught respectively,
- ϕ is the actual angle of heel.

For similar hulls the righting arm GZ, given by:

$$GZ = Y_B\cos\phi + Z_B\sin\phi - Z_G\sin\phi$$

where Z_G is the COG vertical co-ordinate, can be expressed in non-dimensional form as:

$$GZ/B = f(C_V, C_\phi, C_B, f/B, B/T, Z_G/D)$$

where f is the design freeboard and D the depth (fig.1).

Reference is made to I.M.O. recommendations on intact stability of fishing vessels (7) which are summarised in the following criteria:

1 - $GM \geq .35$ m, where GM is the initial metacentric height

2 - $GZ_{30} \geq .20$ m, where GZ_{30} is the rigthing lever at an angle of heel equal to or greater than 30°

3 - $E_{30} \geq .055$ m rad

4 - $E_{40} \geq .090$ m rad

5 - $E_{40} - E_{30} \geq .030$ m rad, where E_{40} and E_{30} are the restoring energies at an angle of heel of 40 resp. 30 degrees; if the downflooding angle ϕ_d is less than 40°, the $E_{\phi d}$ value must be considered.

6 - $\phi_x \geq 25°$ (pref. 30°), where ϕ_x is the angle of heel at which the righting lever GZ is maximum.

The above criteria must be fulfilled for all conditions of loading.

Non-dimensional expressions of the stability indices GM, GZ_{30}, E_{30}, E_{40} and $E_{40}-E_{30}$ referred to in the I.M.O. criteria can be obtained normalizing them by a transverse dimension like the beam, so that the following relationships hold for similar hulls:

$$I_i/B = f(C_V, C_B, f/B, B/T, Z_G/D)$$

where I_i is the generic index for i=1,...5; as regards to the ϕ_x angle, the coefficient $C_{\phi x}$ defined as:

$$C_{\phi x} = (B/T)\tan\phi_x = f(C_V, C_B, f/B, B/T, Z_G/D)$$

has been adopted.

REGRESSION ANALYSIS

The polynomial expressions reported in the following have been obtained by means of regression analysis.

They are in the form:

$$\hat{V} = \Sigma\,A\,V_1^p\,V_2^q\,V_3^r\ldots$$

where

- $\hat{V}$ is the estimated value of a dependent variable,
- $V_1, V_2 \ldots$ are the independent variables,
- $p, q, r \ldots$ the relevant exponents,
- A the coefficients.

Established the significant third order of the regression equation, a SAS software with the procedure MAXR has been adopted, which performs a forward selection to fit the best one-variable model, the best two-variable model, and so on. Variables are switched so that R^2 is maximized.

The analysis has been applied to a sample of 8555 calculated values of the dependent variables, covering the following ranges of the parameters:

$$.6 \leq C_V \leq 1.1$$

$$.554 \leq C_p \leq .700$$

$$2.0 \leq B/T \leq 3.5$$

$$.05 \leq f/B \leq .20$$

$$100 \leq V_o \leq 750\ m^3$$

$$3.75 \leq L/V^{1/3} \leq 5.50$$

In the tables 1, 2 and 3, together with the values of the coefficients and of the exponents, the following quantities are given for each equation:

the mean value of the dependent variable:

$$\bar{V} = \frac{\Sigma_1^n V_i}{n}$$

the standard error:

$$S_E = \sqrt{\frac{\Sigma_1^n (V_i - \hat{V}_i)^2}{n - p}}$$

the correlation coefficient:

$$R^2 = \frac{\Sigma_1^n (\hat{V}_i - \bar{V}_\phi)^2}{\Sigma_1^n (V_i - \bar{V}_\phi)^2}$$

where

- V_i is a generic calculated value of the dependent variable

V_i	is the relevant value estimated by the regression equation	
n	is the total number of the calculated values V_i	
p	is the number of terms in the regression equation	

The ratio of the standard error S_E to the mean value $\bar{V}$ is an evaluation of the mean error which can be committed using the regression equation, while the correlation coefficient gives an indication of how much the variation in the data is explained by the model: if R^2 is equal to unity the regression equation is exactly the functional relationship existing between the variables.

The values of $\bar{V}$, S_E and R^2 reported in the tables 2 and 3 imply that the model fit very well the data (.991 < R^2 < .997) and that on average the error in percentage is less than 2%.

THE RIDGELY NEVITT STANDARD SERIES

The Ridgely-Nevitt standard series of fishing vessels was developed in the 50's (6). The ranges of the main form parameters tested in towing tank were:

C_p = .654 ÷ .700

C_x = .760

$L/V^{1/3}$ = 3.852 ÷ 5.227

B/T = 2.3

For each C_p the series hulls are derived according to similarity law.

Being for this series the C_x coefficient kept constant, in the following the prismatic coefficient C_p is used instead of the block coefficient C_B.

Although only one value of B/T was tested, results can be extended, as suggested by Nevitt, to the B/T range 2 ÷ 3.5 by adopting the correction factors relevant to the B.S.R.A. series.

RESULTS

In a previous paper (9) the analytical non-dimensional expressions providing the I.M.O. stability indices:

$$I_i/B = f(C_V, C_p, f/B, B/T, Z_G/D) \quad i=1,\ldots 5$$

$$C_{\phi x} = f(C_V, C_p, f/B, B/T, Z_G/D)$$

were given in the form:

$$\left.\begin{array}{l} I_i/B \\ C_{\phi x} \end{array}\right\} = \Sigma\ A\ C_p^m\ C_V^n\ (B/T)^p\ (Z_G/D)^q\ (f/B)^r$$

the values of the coefficients A and of the exponents m, n, p, q, r are again reported in table 1.

Dimensional expressions of the first five indices:

$$I_i = f(C_V, C_p, f/B, B/T, Z_G/D, V_o, L/V^{1/3}) \quad i=1,\ldots 5 \qquad (1)$$

were then obtained using the relationship:

$$B = ((V_o^{2/3}/(L/V^{1/3})\ ((B/T)/C_B))^{1/2} \qquad (2)$$

As regards to the sixth criterion obviously it holds:

$$\tan \phi_x = C_{\phi x}\ /(B/T) \qquad (3)$$

The maximum allowable Z_G/D_i value which fulfils the ith criterion I_i has then been obtained by solving eq.s (1) and (3) with respect to Z_G/D and substituting for I_i and ϕ_x the minimum value required in the I.M.O. recommendations; such Z_G/D_i values are a function of the independent variables according to:

$$Z_G/D_i = f(C_V, C_p, f/B, B/T, V_o, L/V^{1/3}) \quad i=1,\ldots 5$$

$$(4)$$

$$Z_G/D_i = f(C_V, C_p, f/B, B/T) \quad i=6$$

The first five equations can be easily deduced by eq.s (1) and (2) being the former ones linear in Z_G/D (see table 1). The Z_G/D_6 values are instead solutions of the third order equation (3); these values have been calculated for a suitable number of points and expressed by means of regression analysis in the usual form:

$$Z_G/D_6 = \Sigma\ A\ C_p^m\ C_V^n\ (B/T)^p (f/B)^q \qquad (5)$$

the relevant exponents and coefficients are reported in table 2.

The above relationships allow to compare the I.M.O. criteria in a very effective and concise manner: in fact, for a given set of the independent variables, it is possible to determine what is the most severe criterion, that is the criterion which limits the allowable value of COG heigth.

For instance for the hull having the following main dimensions:

C_p = .600 $\quad L/V^{1/3}$ = 4.800

B/T = 2.3 $\quad$ f/B = .11

V_o = 300 m^3

at full load condition (i.e. C_V = 1.) the maximum Z_G/D_i values which fulfil I.M.O. criteria are:

criterion n°		Z_G/D_i
1	GM	.83
2	GZ_{30}	.73
3	E_{30}	.79
4	E_{40}	.76
5	$E_{40} - E_{30}$	.72
6	ϕ_x	.67

In this case the Z_G/D maximum value relevant to the ϕ_x criterion is far less than the other ones.

In order to verify the stability of the hull to be designed, only the knowledge of the maximum value of the Z_G/D ratio imposed by the most severe criterion needs; this value is minimum one among the six Z_G/D_i given by equations (4), which satisfies simultaneously all the stability criteria.

By means of the regression analysis the expression of the ratio Z_G/D_{max} which satisfies the first five I.M.O. criteria has been determined in the form:

$$Z_G/D_{max} = \Sigma\ A\ C_p^m\ C_v^n\ (B/T)^p\ \nabla_o^q\ (f/B)^r\ (L/\nabla^{1/3})^s \qquad \text{(eq. 6)}$$

the relevant exponents and coefficients are reported in table 3.

The last criterion, ϕ_x, is fulfilled if Z_G/D is less than the value given by equation (5).

This last criterion has not been considered in deriving equation (6) because for it the Z_G/D_i value does not depend on ∇_o and $L/\nabla^{1/3}$ as for the other criteria.

Equations (5) and (6) allow to very quickly verify the stability of a Ridgely-Nevitt hull .

In fact if the foreseen Z_G/D value is less than the minimum between the values given by these equations, the I.M.O. criteria are fulfilled.

Fig.s from 2 to 9 show the pattern of the Z_G/D_i curves.

Fig.s 2, 3 and 4 show the Z_G/D_i values at full load condition for all the criteria (eq.s 4) as a function of ∇_o, f/B and B/T resp., being the other variables kept constant. The Z_G/D_{max} curves given by eq. (6) are plotted as well.

It is interesting to compare the ϕ_x criterion with the other ones.

Because the $C_{\phi x}$ coefficient does not depend on the design displacement volume, the ϕ_x criterion cannot be met increasing the value of this variable; at f/B = .11, which is a typical value for this kind of vessel, the ϕ_x criterion is the most severe one for any ∇_o (fig.2). It should be noted that for B/T = 2.3, the value tested in towing tank, and the abovesaid typical value of f/B, the maximum allowable value of the Z_G/D ratio is quite low (about .67); increasing f/B this value increses up to f/B ≈ .15, behind this value the other criteria prevail and the Z_G/D_{max} ratio decreases with f/B (fig.3).

Of course, increasing B/T improves stability (fig.4), but the ϕ_x criterion remains the limiting one at full load condition.

This situation changes at light load condition (i.e. $C_v < 1$): fig.s 5 and 6 show the curves of Z_G/D_{max} according to eq. (6) (first five criteria) and to eq. (5) (ϕ_x criterion). The allowable Z_G/D value increases as C_v decreases; the ϕ_x criterion is still the most severe one if C_v is greater than a value depending mainly on f/B and B/T: this value increases as f/B increases, but decreases as B/T increases as show in fig.s 5 and 6.

Fig.s 7 and 8 show the influence of the design displacement volume at C_v = .7 and .9 respectively; in particular from fig.8 it can be deduced that, for f/B = .11 and B/T = 2.3 the allowable Z_G/D value decreases very markedly as ∇_o decreases under 200 m^3, because in this case the limiting criteria are the first five ones.

CONCLUSIONS

The proposed equations for the maximum value of the center of gravity to depth ratio which fulfils all the stability criteria recommended by I.M.O. allow a very quick judgement of the stability of a hull derived from the Ridgely-Nevitt standard series.

They are particularly useful in an automated procedure of hull optimization, because they represent in a very simple and time saving manner the restrain constituted by the stability evaluation to the choice of the main hull dimensions.

Moreover, by means of these equations it is possible to analyse the influence on stability of the design parameters and to compare the relative severity of the I.M.O. criteria.

Although they were derived for the Ridgely-Nevitt series, the authors feel that they could be also applied to hulls not derived from this series but of similar form.

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m_i	n_i	p_i	q_i	r_i	GM/B	$GZ_{30°}/B$	$C_{\phi\ max}$	$E_{30°}/B$	$E_{40°}/B$	$(E_{40°}-E_{30°})/B$
0	0	0	0	0	-1.373358	-0.000719	12.28898	-0.048152	-0.080586	0.014146
1	0	0	0	0	8.854319	1.129956	-5.911244	0.517234	0.711545	0.188851
0	1	0	0	0	-0.577931	0.102281	-21.62323	0	0	0
0	0	1	0	0	0.092408	0.009239	0.181200	0.008088	0.053966	0
0	0	0	1	0	-1.066248	-0.555855	-6.806017	-0.148440	-0.242641	-0.106494
0	0	0	0	1	0	-0.351764	0	-0.171308	-0.242327	-0.048488
2	0	0	0	0	-16.61651	-2.064608	0	-1.075309	-1.414271	-0.345672
0	2	0	0	0	0.065467	-0.095847	21.05310	0	0	0
0	0	2	0	0	-0.010656	0	0	0	-0.013544	0
0	0	0	2	0	0	0	0	0	0	0
0	0	0	0	2	0	-2.783161	87.90471	-0.368480	-0.937600	-0.566278
3	0	0	0	0	10.434982	1.389057	0	0.721836	0.955689	0.232508
0	3	0	0	0	0	0	-5.803230	-0.020682	-0.023647	-0.003059
0	0	3	0	0	0.002324	0	0	0	0.001283	0
0	0	0	3	0	0	0	-1.884016	0	0	0
0	0	0	0	3	0	9.809514	87.15120	3.945787	5.412894	1.447660
1	1	0	0	0	3.321618	0.345724	9.467338	0.282488	0.346117	0.059409
1	0	1	0	0	0.081758	0	0	0.014870	0.003410	-0.000410
1	0	0	1	0	0	0	0	0	0	0
1	0	0	0	1	0	0	0	0.154066	0.227462	0
0	1	1	0	0	-0.217634	-0.112097	0.156942	-0.043538	-0.063791	-0.019322
0	1	0	1	0	0	0	0	0	0	0
0	1	0	0	1	0	1.115929	-17.80267	0.112304	0.302949	0.190371
0	0	1	1	0	0.373784	0.206603	0.358712	0.054481	0.083489	0.037591
0	0	1	0	1	0	0.106223	2.338212	0.035435	0.065964	0.030513
0	0	0	1	1	-0.999719	-0.517526	0	-0.133612	-0.234999	-0.101096
0	0	0	1	2	0	0	-88.33043	0	0	0
0	2	0	1	0	0	0	-7.525888	0	0	0
2	0	0	1	0	0	0	2.122701	0	0	0
0	0	2	1	0	-0.043104	-0.025297	0	-0.006617	-0.009514	-0.004364
0	0	0	2	1	0	0	8.987825	0	0	0
0	2	0	0	1	0	0.274078	18.15156	0.330767	0.342809	0.012092
2	0	0	0	1	0	0.370125	3.935531	0	0	0.057148
0	0	2	0	1	0	0.009884	0	0	0	0
0	1	0	2	0	0	0	8.534763	0	0	0
0	1	0	0	2	0	-2.802224	-46.73594	-1.672401	-1.953708	-0.280495
2	1	0	0	0	-2.992592	-0.426022	0	-0.247087	-0.317960	-0.067986
0	1	2	0	0	0.017378	0.013155	0	0.004999	0.007493	0.002335
1	0	0	0	2	0	-1.081649	-37.71681	-0.430564	-.0593715	-0.156321
1	2	0	0	0	0	0	-5.218114	-0.019306	-0.024021	-0.004359
1	0	2	0	0	0	0	-0.055736	-0.001889	0	0
ROOT MSE					0.00094	0.00073	0.04642	0.00041	0.00044	0.00011
DEP MEAN					0.18772	0.05772	1.64762	0.01978	0.02955	0.00977
R-SQUARE					0.9999	0.9994	0.9937	0.9981	0.9991	0.9996

TAB. 1

m_i	n_i	p_i	q_i	Cφ 25°
0	0	0	0	2.817270
1	0	0	0	1.557449
0	1	0	0	-5.052845
0	0	1	0	-0.709179
0	0	0	1	-4.462020
2	0	0	0	-6.075134
0	2	0	0	0.417963
0	0	2	0	0.168896
0	0	0	2	21.735594
1	1	0	0	6.883042
1	0	1	0	-0.702684
1	0	0	1	-3.389488
0	1	1	0	1.236796
0	1	0	1	8.972157
0	0	1	1	0.234853
3	0	0	0	3.031796
0	3	0	0	1.392871
0	0	3	0	-0.020965
0	0	0	3	-42.763659
1	2	0	0	-2.444441
1	0	2	0	-0.051915
1	0	0	2	-28.169639
0	1	2	0	0.010930
0	1	0	2	17.025353
0	0	1	2	-3.596457
2	1	0	0	-1.822385
2	0	1	0	0.834389
2	0	0	1	7.277172
0	2	1	0	-0.701471
0	2	0	1	-6.232453
0	0	2	1	0.316143
1	1	1	0	-0.221291
1	1	0	1	-1.859364
1	0	1	1	1.159040
0	1	1	1	-0.574515
ROOT MSE				0.01521
DEP MEAN				0.80922
R-SQUARE				0.99070

Tab. 2

m_i	n_i	p_i	q_i	r_i	s_i	MIN 25°
0	0	0	0	0	0	-1.077581
1	0	0	0	0	0	4.509657
0	1	0	0	0	0	-0.095400
0	0	1	0	0	0	0.668166
0	0	0	1	0	0	0.000309
0	0	0	0	1	0	0.507584
0	0	0	0	0	1	0.668166
2	0	0	0	0	0	-8.628317
0	2	0	0	0	0	0.370486
0	0	2	0	0	0	-0.112442
0	0	0	2	0	0	-0.000001
0	0	0	0	2	0	-18.247317
0	0	0	0	0	2	-0.000788
1	1	0	0	0	0	1.923476
1	0	1	0	0	0	0.029706
1	0	0	1	0	0	0.000310
1	0	0	0	1	0	-1.017602
1	0	0	0	0	1	-0.037527
0	1	1	0	0	0	-0.293254
0	1	0	1	0	0	0.000135
0	1	0	0	1	0	-0.051352
0	1	0	0	0	1	-0.014769
0	0	1	1	0	0	-0.000010
0	0	1	0	1	0	0.219362
0	0	1	0	0	1	0.001067
0	0	0	1	1	0	-0.000091
0	0	0	1	0	1	0.000013
0	0	0	0	1	1	0.016361
3	0	0	0	0	0	5.886164
0	3	0	0	0	0	-0.405685
0	0	3	0	0	0	0.015853
0	0	0	3	0	0	0.000000
0	0	0	0	3	0	32.964675
0	0	0	0	0	3	0.000111
2	1	0	0	0	0	-2.154178
2	0	1	0	0	0	-0.003448
2	0	0	1	0	0	-0.000198
2	0	0	0	1	0	1.358209
2	0	0	0	0	1	0.024298
1	2	0	0	0	0	0.004184
0	2	1	0	0	0	0.014555
0	2	0	1	0	0	-0.000095
0	2	0	0	1	0	2.086988
0	2	0	0	0	1	0.009678
ROOT MSE						0.00576
DEP MEAN						0.75635
R-SQUARE						0.99700

Tab. 3

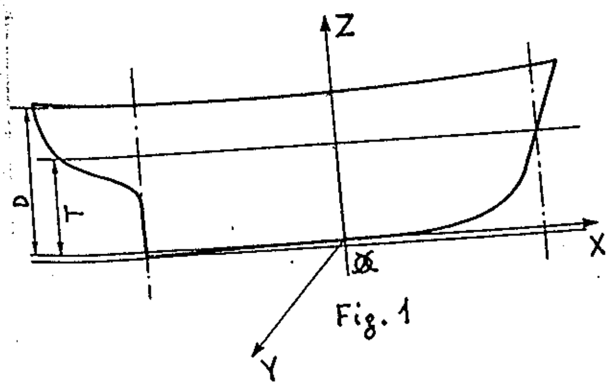

Fig. 1

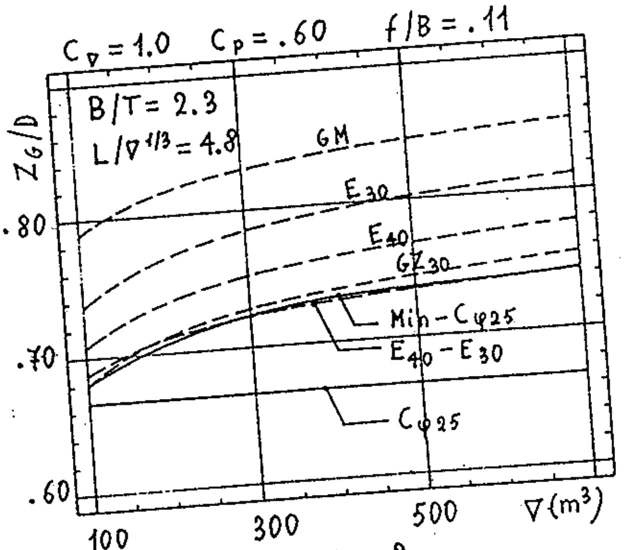

Fig. 2

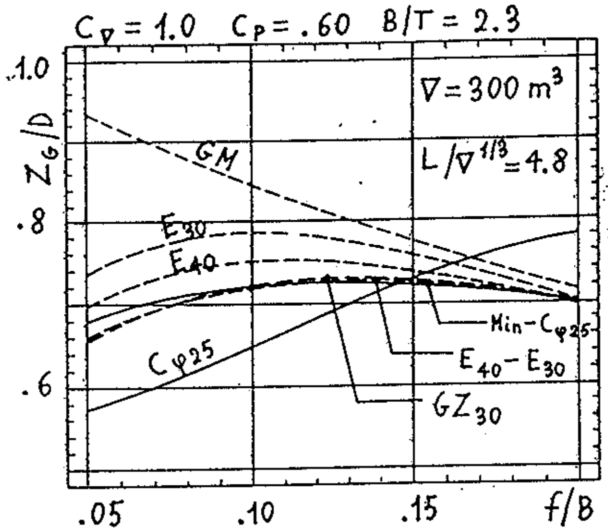

Fig. 3

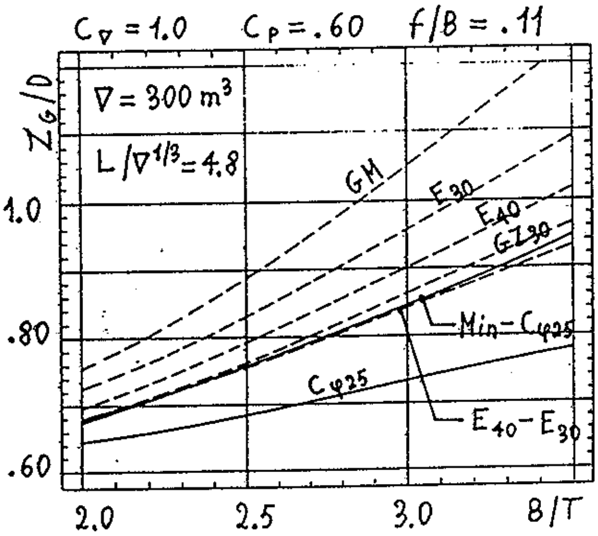

Fig. 4

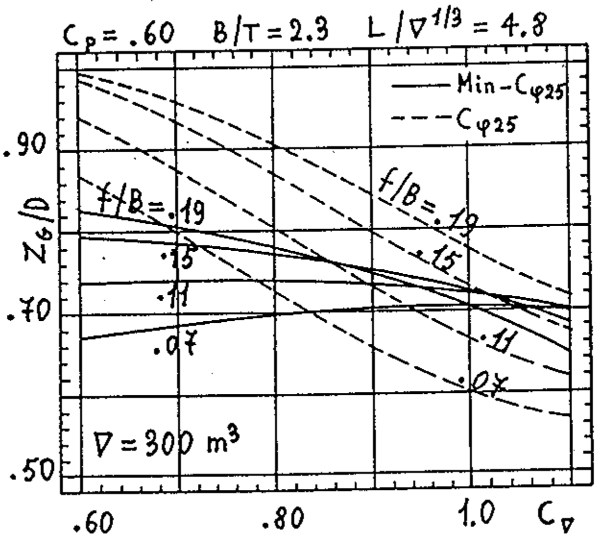

Fig 5

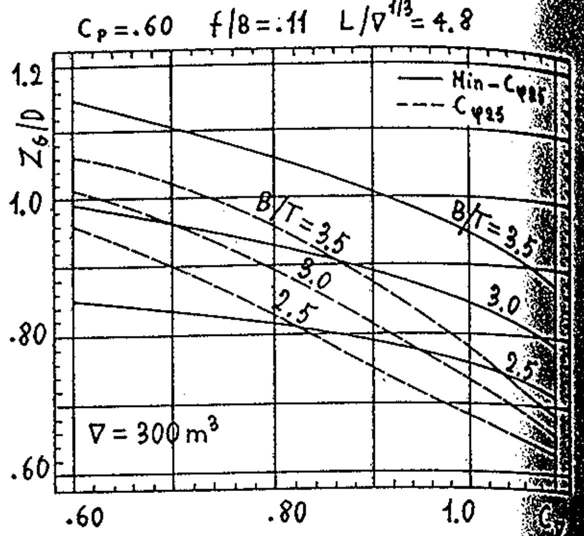

Fig. 6

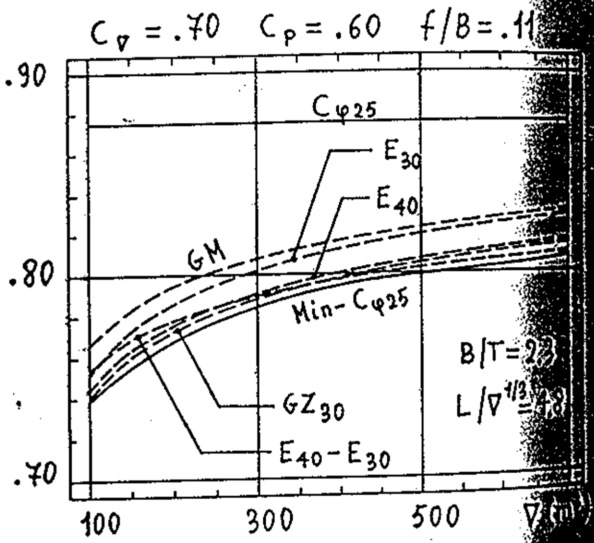

Fig. 7

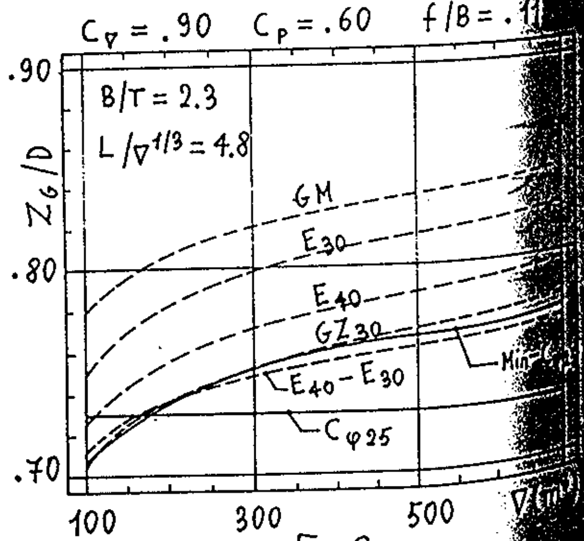

Fig 8