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Investigations of transverse stability of semi--displacement ships

SUMMARY

In this paper results of experimental model investigations of transverse stability of semi--displacement ships are presented, aimed at determination of influence of their speed and hull form parameters on transverse stability. On the basis of these results algorithms were elaborated which take into account righting arm changes in function of ship speed, heel angle and geometrical hull parameters. The algorithms can be used for assessment of transverse stability of ships of the kind.

INTRODUCTION

The semi-displacement ships commonly used for fast civil and military transport are characterized of round-bottom hull form and the speed range determined by displacement-related Froude number value from 1.2 ÷ 3.0 range. Their weight is balanced mainly by buoyancy and partly – depending on speed – by hydrodynamic supporting forces. In operation, especially at high speeds an unfavourable phenomenon of spontaneous increasing heel angle occurs which impairs ship safety. Causes of the phenomenon are not sufficiently known and hence International Maritime Organisation (IMO) regulations reccommend to experimentally test transverse stability of any prototype ship of the kind. In the 21st International Towing Tank Conference (ITTC) report urgent need of initiation of research in this area is stressed. From literature survey it results that the phenomenon in question was the subject of isolated model tests carried out by National Physical Laboratory (NPL) in Great Britain [1] and by VWS (Versuchsanstalt für Wasserbau und Shiffbau-Berlin) in Germany [2] and it was also observed on real ships. Therefore to undertake systematic research on determination of influence of ship hull parameters on transverse stability of semi-displacement ships in still water conditions and in the above mentioned speed range, was deemed reasonable. The presented investigations were carried out by the Department's team in the towing tank of Ship Hydrodynamics Department, Faculty of Ocean Engineering and Ship Technology, Gdańsk University of Technology, in the frame of the research project no. 9T12C03520 financed by the State Committee for Scientific Research (KBN).

AIM AND METHODS OF THE INVESTIGATIONS

The investigations were aimed at determination of influence of speed and hull form parameters on transverse stability of the considered ships. They were carried out for a series of 5 affined models of a constant-length waterline and different B/L and B/d ratios. Measurements were performed by using a method consisting in application of an initial heeling moment and recording heel angle changes in function of ship speed. As a result of the research the algorithms were elaborated which make it possible to determine righting arm changes in function of hull form parameters, ship speed defined by the displacement-related Froude number, heel angles and initial metacentric height related to ship draught.

CHARACTERISTICS OF THE INVESTIGATED MODEL SERIES

A hull form basic for the entire series was selected on the basis of analysis of available hull forms of existing military and civil ships of the kind. The selected hull form had favourable resistance and stability characteristics both in still water and in waves. Four models of changeable B/d ratio were designed by assuming – for the entire series – a constant--length design waterline at a given displacement. Thus, the series of five geometrically affined models consisted of the four models and the basic one. The range of changes of geometrical parameters of the model series is given in Tab.1 for the design-displacement state and in Tab.2 for a light-displacement state.

***Tab.1.** Geometrical hull parameters of the investigated series of models*
– for the design-displacement state

Symbol	L_o [m]	L [m]	B / d [-]	$L/\nabla^{1/3}$ [-]	Δ [kg]	C_B [-]	z_G [m]	h_o / d [-]	B / L [-]
Model 1	1.358	1.250	2.50	6.616	6.754	0.445	0.079	0.314	0.139
Model 2			3.00					0.593	0.153
Model 3			3.37					0.833	0.162
Model 4			4.00					1.327	0.176
Model 5			4.50					1.788	0.187

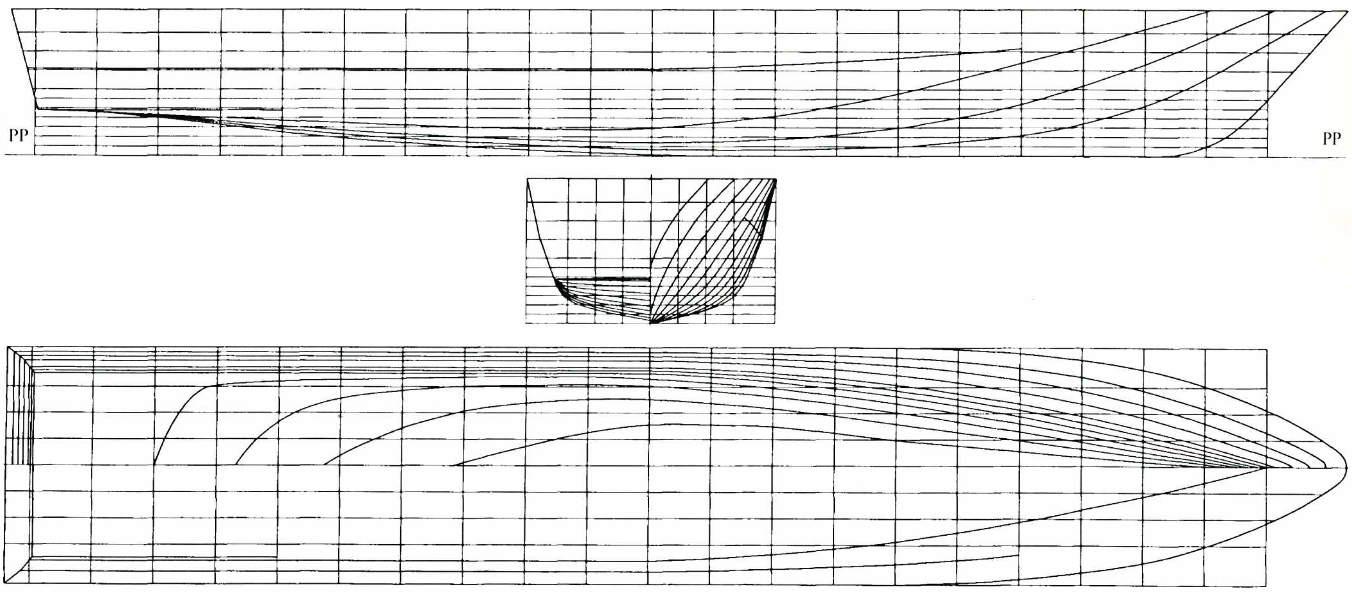

Fig.1. A sketch of body lines of the basic model – 3

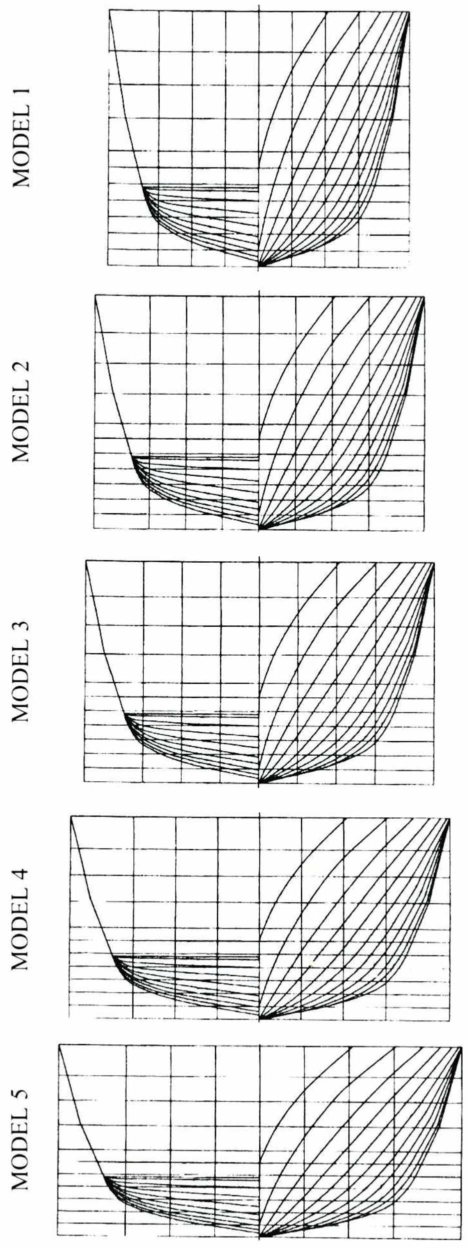

Fig.2. Frame sections of the considered model series

Tab.2. Geometrical hull parameters of the investigated series of models
– for the light-displacement state

Symbol	L_o [m]	L [m]	B / d [-]	$L/\nabla^{1/3}$ [-]	Δ [kg]	C_B [-]	z_G [m]	h_o / d [-]	B / L [-]
Model 1			2.67					0.375	0.137
Model 2			3.22					0.724	0.150
Model 3	1.358	1.246	3.62	6.960	5.740	0.421	0.079	1.000	0.159
Model 4			4.25					1.568	0.174
Model 5			4.79					2.146	0.184

A sketch of body lines of the model – 3 basic for the entire series is presented in Fig.1, and the frame sections of the particular models of the series – in Fig.2.

WAY AND RANGE OF THE EXPERIMENTAL INVESTIGATIONS

The model was mounted to a head which made free heaving, heeling and trimming possible. Rotation of the model around the vertical axis was blocked at zero drift angle. The righting arm curve $l = l_0(\varphi)$ was determined for the model in rest. The model was towed successively at three values of the heeling moment causing the initial heel angles : $\varphi_{0i} = 2^0$, 4^0, and 5^0 and two displacement states : design and light one. The moments were applied successively to port and starboard. The trials were carried out in the range of the towing speed V from 0.40 to 3.0 m/s, which corresponded with the displacement--related Froude number $Fn_V = 0.29 \div 2.2$. The stationary heel angle value φ_{iv} was recorded at each speed.

The above presented testing cycle was repeated for all models of the series.

RESULTS OF INVESTIGATIONS

The speed-dependent values of the heel angles φ_v, obtained from experiments, are presented – in the form shown in Fig.3 – for every M_{pi} heeling moment value and corresponding to it value of the heeling arm l_{pi}, together with the characteristics of changes of the static righting arm $l = l_0(\varphi)$. The characteristics of the righting arms $l_u = l_u(\varphi_{iv}) \mid_{V = const}$ were determined by means of interpolation of the heel angle φ_{iv} for the heeling arm l_{pi}.

The change of the speed-dependent righting arms was defined as follows :

$$\Delta l = l_0(\varphi) - l_u(\varphi) \tag{1}$$

The Δl value related to that of the static righting arm $l = l_0(\varphi)$ is in compliance with the following expression :

$$\frac{\Delta l}{l} = \frac{l_0(\varphi) - l_u(\varphi)}{l_0(\varphi)} = 1 - \frac{l_u(\varphi)}{l_0(\varphi)} \tag{2}$$

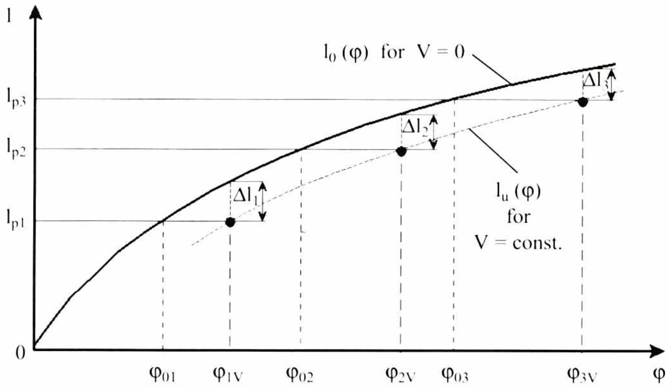

Fig.3. *A scheme of determination of the righting arms $l_u = l_u(\varphi_{iV})$*

Changes of the righting arm were presented, by taking into account influence of the initial metacentric height h_0, in the form of the diagrams $(\Delta l/l * h_0/d * C_B) = f(B/L)$ shown in Fig.4. to 9. as well as of those $(\Delta l/l * h_0/d * C_B) = f(B/d)$ – in Fig.10. to 15. for constant values of the heel angle φ, relative velocity (Froude number) Fn_∇ and both considered displacement states. In all the figures, i.e. Fig.4 to 15, the symbols given at Fn_∇ values relate to, respectively :

k - design-displacement state and
l - light-displacement state.

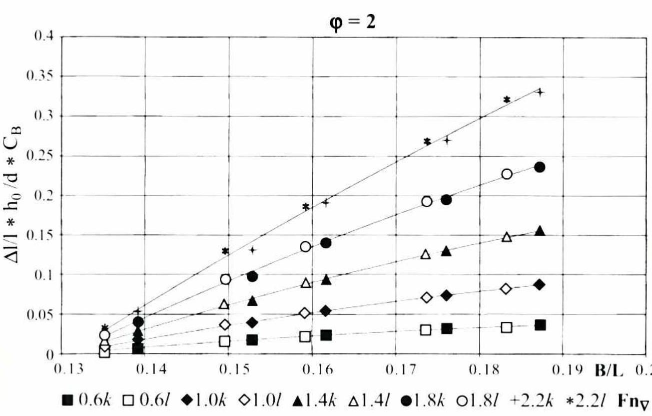

Fig.4. *The diagram of the coefficient $(\Delta l/l * h_0/d * C_B) = f(B/L)$ for φ = 2*

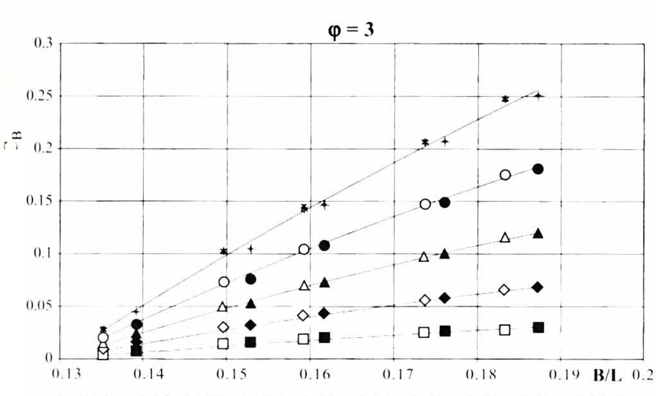

Fig.5. *The diagram of the coefficient $(\Delta l/l * h_0/d * C_B) = f(B/L)$ for φ = 3*

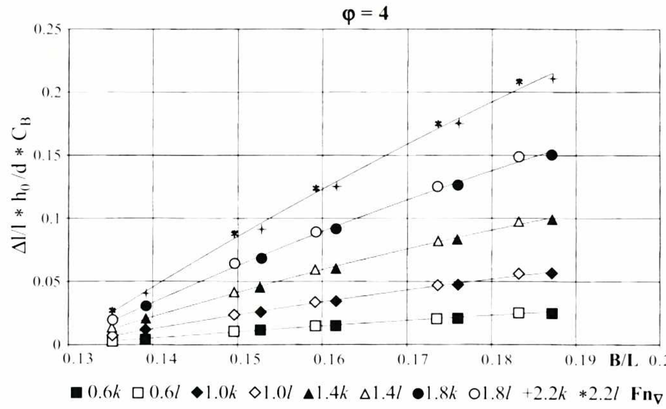

Fig.6. *The diagram of the coefficient $(\Delta l/l * h_0/d * C_B) = f(B/L)$ for φ = 4*

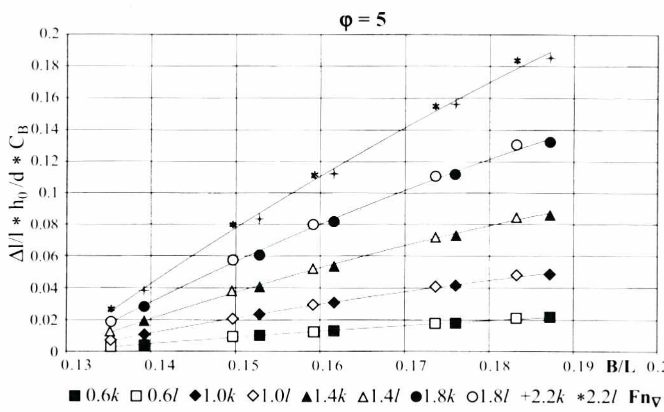

Fig.7. *The diagram of the coefficient $(\Delta l/l * h_0/d * C_B) = f(B/L)$ for φ = 5*

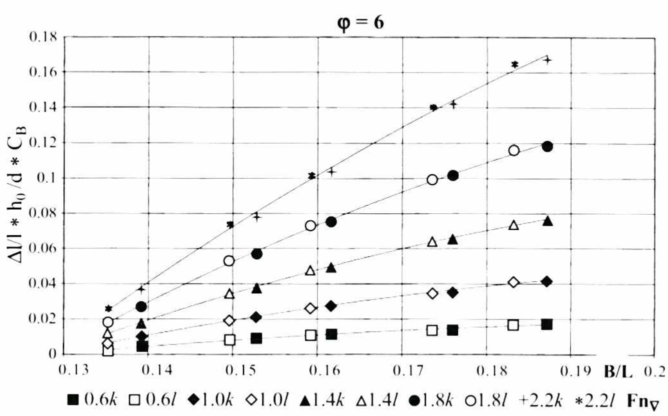

Fig.8. *The diagram of the coefficient $(\Delta l/l * h_0/d * C_B) = f(B/L)$ for φ = 6*

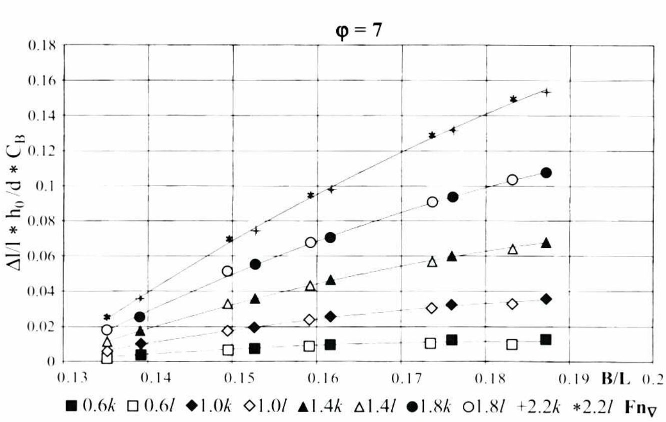

Fig.9. *The diagram of the coefficient $(\Delta l/l * h_0/d * C_B) = f(B/L)$ for φ = 7*

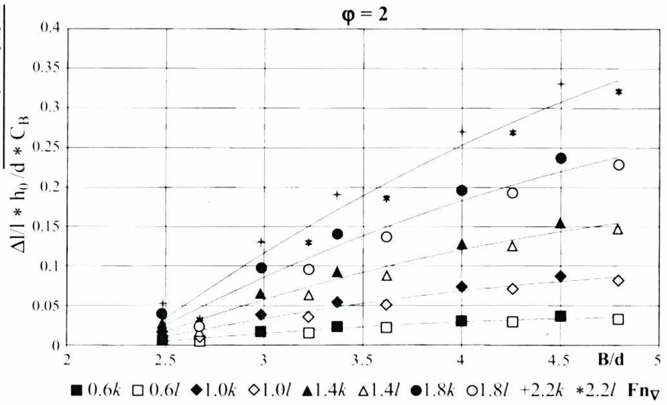

Fig.10. The diagram of the coefficient
$(\Delta l/l * h_0/d * C_B) = f(B/d)$ *for* $\varphi = 2$

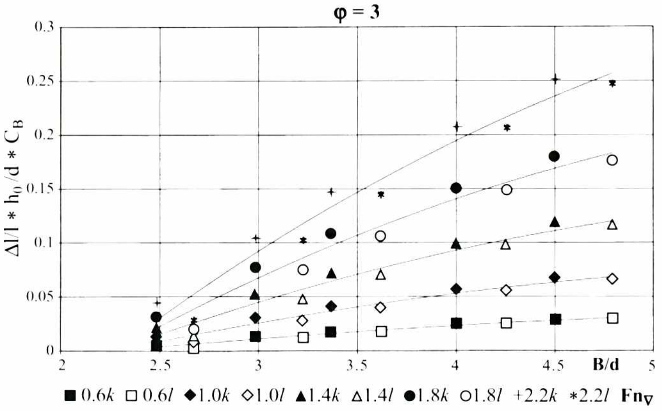

Fig.11. The diagram of the coefficient
$(\Delta l/l * h_0/d * C_B) = f(B/d)$ *for* $\varphi = 3$

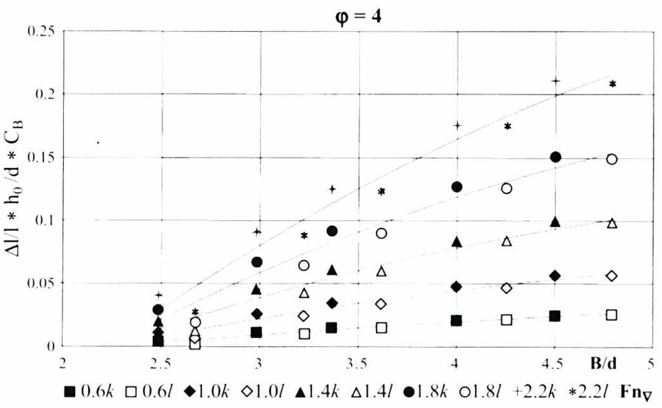

Fig.12. The diagram of the coefficient
$(\Delta l/l * h_0/d * C_B) = f(B/d)$ *for* $\varphi = 4$

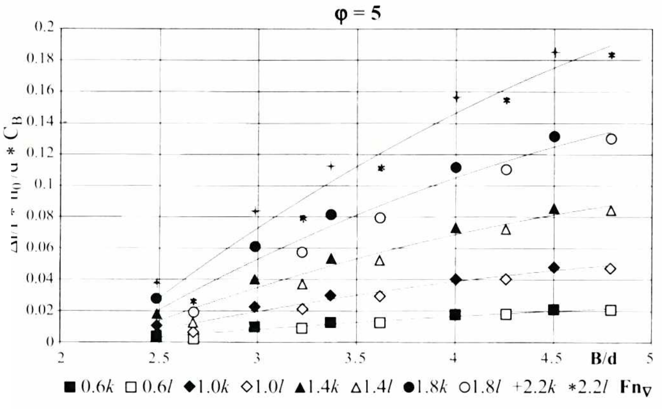

Fig.13. The diagram of the coefficient
$(\Delta l/l * h_0/d * C_B) = f(B/d)$ *for* $\varphi = 5$

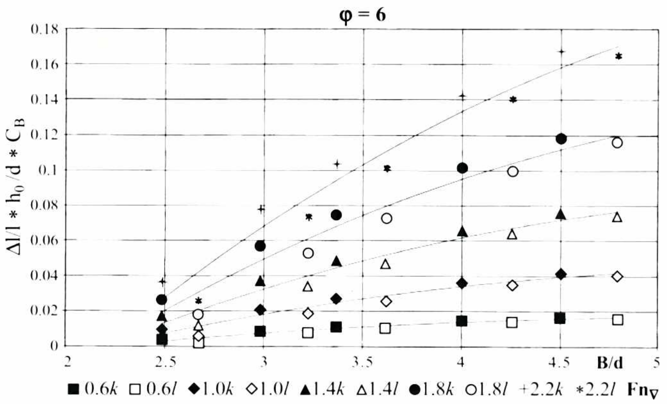

Fig.14. The diagram of the coefficient
$(\Delta l/l * h_0/d * C_B) = f(B/d)$ *for* $\varphi = 6$

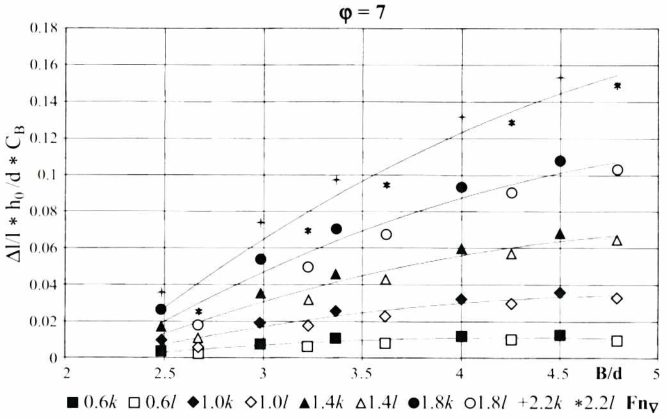

Fig.15. The diagram of the coefficient
$(\Delta l/l * h_0/d * C_B) = f(B/d)$ *for* $\varphi = 7$

ANALYSIS OF RESULTS AND CALCULATION ALGORITHMS

Influence of B/L ratio on magnitude of change of the speed-dependent righting arms

In Fig.4÷9 character of changes of the righting arm is shown for the heel angles $\varphi = 2°÷7°$, relative velocity (Froude number) $Fn_\nabla = 0.6$, 1.0, 1.4, 1.8, and 2.2 and both displacements.

From analysis of the above presented characteristics the following conclusions can be drawn :

- ➔ respective values of $(\Delta l/l * h_0/d * C_B)$ are the same for both displacement states
- ➔ $(\Delta l/l * h_0/d * C_B)$ values increase along with increase of values of B/L ratio, relative velocity (Froude number) Fn_∇ for all considered heel angle values
- ➔ for constant value of B/L ratio $(\Delta l/l * h_0/d * C_B)$ values decrease along with increase of values of the heel angle φ
- ➔ functions $(\Delta l/l * h_0/d * C_B) = f(B/L)$ can be straight-line approximated in the considered range of changes of B/L ratio and relative velocity (Froude number) Fn_∇, for all considered values of of the heel angle φ.

Algorithm for calculation of $\Delta l/l = f(\varphi, Fn_\nabla, B/L, h_0/d, C_B)$

On the basis of the obtained results the interpolating algorithm (3) was elaborated for approximate calculation of $\Delta l/l$, valid within the following limits of parameters :

$$\varphi = 2° \div 7°$$

$$Fn_{\nabla} = 0.4 \div 2.2$$

$$L/\nabla^{3} = 6.614 \div 6.960$$

$$h_0/d = 0.314 \div 0.445$$

$$B/L = 0.135 \div 0.197$$

$$\begin{aligned}\frac{\Delta}{l} = \Big\{ & \left(-0.0548 - 0.0073 \cdot \varphi + 0.00217 \cdot \varphi^2\right) \cdot Fn + \\ & -\left(0.1767 - 0.03839 \cdot \varphi + 0.0032 \cdot \varphi^2\right) \cdot Fn^2 + \\ & + \Big[\left(0.50083 + 0.02843 \cdot \varphi - 0.0136 \cdot \varphi^2\right) \cdot Fn + \\ & + \left(1.32448 - 0.2772 \cdot \varphi + 0.0231 \cdot \varphi^2\right) \cdot Fn^2\Big] \cdot \\ & \cdot \left(\frac{B}{L}\right)\Big\} \cdot \left(\frac{d}{h_o} \cdot \frac{1}{C_B}\right)\end{aligned} \tag{3}$$

Respective changes of the righting arm for the relative velocity (Froude number) $Fn_{\nabla} = 2.2$ are as follows :

at the heel angle $\varphi = 3°$

$\Delta l/l = 0.318 \div 0.397$ – for the design displacement
$\Delta l/l = 0.182 \div 0.345$ – for the light-state displacement

at the heel angle $\varphi = 7°$

$\Delta l/l = 0.193 \div 0.256$ – for the design displacement
$\Delta l/l = 0.159 \div 0.225$ – for the light-state displacement.

Average discrepances between calculated from (3) and experimental values appeared not greater than 5%.

Influence of B/d ratio on magnitude of change of the speed-dependent righting arms

In Fig.10÷15 character of changes of the righting arm coefficient ($\Delta l/l * h_0/d * C_B$) = f(B/d) is shown for B/d ratio = 2.50 ÷ 4.79. The variability limits of the remaining parameters are the same as in the preceding case.

Algorithm for calculation of $\Delta l/l = f(\varphi, Fn_{\nabla}, B/d, h_0/d, C_B)$

In this case an interpolating function took the following form :

$$\begin{aligned}\frac{\Delta}{l} = \Big\{ & \left(-0.0085 - 0.0075 \cdot \varphi + 0.00137 \cdot \varphi^2\right) \cdot Fn + \\ & -\left(0.0717 - 0.01697 \cdot \varphi + 0.0015 \cdot \varphi^2\right) \cdot Fn^2 + \\ & + \Big[\left(0.00966 + 0.00136 \cdot \varphi - 0.0004 \cdot \varphi^2\right) \cdot Fn + \\ & + \left(0.03043 - 0.0065 \cdot \varphi + 0.00055 \cdot \varphi^2\right) \cdot Fn^2\Big] \cdot \\ & \cdot \left(\frac{B}{d}\right)\Big\} \cdot \left(\frac{d}{h_o} \cdot \frac{1}{C_B}\right)\end{aligned} \tag{4}$$

Maximum discrepances between calculated from (4) and experimental values appeared similar as in the case of the algorithm (3).

CONCLUSIONS

- The performed experimental investigations confirmed the ocurrence of the unfavourable phenomenon of spontaneous increase of heel angle along with increase of speed for all considered models; the greater B/L and B/d the less distinct that phenomenon. Also, decrease of ship's displacement appeared favourable.
- Change of vertical position of ship's centre of gravity had greater influence on ship's transverse stability than change of geometrical hull form parameters.
- The elaborated calculation algorithms can be used for transverse stability assessment of the semi-displacement ships.
- The applied investigation method can be deemed an effective tool for testing the transverse stability of the semi-displacement ships.

Appraised by Jan A. Szantyr, Prof.,D.Sc.,N.A.

NOMENCLATURE

b – balast weight shift [m] B – water line breadth [m]
C_B – block coefficient [-]
d – ship draught [m]
Fn_{∇} – displacement-related Froude number - $Fn_{\nabla} = V/\sqrt{g \cdot \nabla^{1/3}}$ [-]
g – acceleration of gravity [m/s²]
h_0 – initial metacentric height [m]
l – righting arm curve – $l = l_0(\varphi)$ l_0 – righting arm of model in rest (V=0) [m]
l_{pi} – heeling arm [m] – $l_{pi} = M_{pi}/\Delta * b$ l_u – speed-dependent righting arm [m]
Δl – change of righting arm value – $\Delta l = l_0 - l_u$ [m]
L_0 – overall length of model [m]
L – water line length [m]
M_{pi} – heeling moment – $M_{pi} = p_B * b * \cos\varphi_{0i}$ [Nm]
p_B – balast weight value [N]
V – model speed [m/s]
z_G – height of centre of gravity of model over its reference plane PP [m]
∇ – model displacement [m³] Δ – model mass [kg]
φ – heel angle [°]
φ_{0i} – static heel angle [°] due to M_{pi} moment
φ_{iv} – heel angle [°] for heeling arm l_{pi} and model speed V

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3. Brzoska E., Grygorowicz M., Rogalski A.: *Analysis of experimental investigations of series of a semi-displacement ship* (in Polish). Research report No. 21/2002/PB. Faculty of Ocean Eng. and Ship Techn., Gdańsk University of Technology. 2002

FOREIGN *conference*

PACIFIC 2002

On 29-31 January 2002 International Maritime Conference was held in Sydney. Two Polish scientific workers from sea-coast universities also cotributed to its program. They prepared the following papers :

- *Asymptotic aproach to reliability and risk evaluation of port and shipyard transporation systems* – by K.Kołowrocki, Gdynia Maritime University
- *Modelling a seagoing ship operation process as the part of ship's safety model* – by A. Brandowski, Gdańsk University of Technology, and K.Kołowrocki, Gdynia Maritime University.

Both papers were published in the Proceedings of the Conference.