A parametric method for preliminary determining of mass characteristics of inland navigation ships

Jan P. Michalski
Gdańsk University of Technology

ABSTRACT

This paper presents a method for estimation of mass characteristics of vessels, elaborated with the use of an algorithm based on requirements of the Rules for the Classification and Construction of Inland Waterways Vessels of Polish Register of Shipping, and on a simplified method [6] for determination of mass of hull plating stiffeners. The dimensioning method of hull structure scantlings based on this algorithm concerns classical vessels intended for the carrying of general cargo, dry and liquid bulk cargoes, which determine the range of the method application. The method does not cover vessels of different construction, e.g. roll-on-roll-off type vessels equipped with heavy decks, as the dimensioning of their scantlings is based on different relationships and models.

Keywords : Inland waterways vessels, ship preliminary design methods

INTRODUCTION

Methods for preliminary, approximate estimation of mass as well as mass centre coordinates of a designed ship is an important branch of ship design theory. Knowledge of the parameters is necessary already in early design phases – to iteratively balance ship's floatability and stability before structural strength calculations are performed.

The subject-matter literature contains some methods concerning this subject, e.g. in [1, 2, 3, 4] and [5], which, however, deal with sea-going ships whose features are different from those of inland waterways vessels. The methods applicable to inland waterways vessels are rather scarce, e.g. [6, 7, 8, 9, 10].

In the preliminary design stage, ship mass and its centre of gravity are usually estimated by means of the methods making use of parent ship's data, if only they are available. In the case when such data are lacking, or if a design project covers a broad range of variability of ship design parameters, e.g. in a design optimization study (with a selected objective function), then use of general parametric methods is necessary to determine ships mass characteristics.

The parametric methods for estimating ship hull mass are elaborated on the basis of either statistical data of existing ships or the rules of classification societies.

A range of applicability of such methods is usually limited by the following factors :

- ship's functional type
- hull structural arrangement
- structural material
- ship's size range.

To elaborate the presented method a set of discrete values of mass of vessel's hull series of systematically varying parameters was simulated by means of the computer implementation [14] of the algorithm [13]. Next, correlations between the hull parameters and their mass characteristics were investigated, which made it possible to reduce some number of unimportant parameters appearing in the problem. Next, analytical relationships approximating the discrete values of mass characteristics were determined. Simulating calculations were carried out for assumed parameters of normal strength (NW) steel – – usually applied for construction of hulls of inland waterways vessels.

The problem is to determine an analytical mathematical model to transform those vessel's features which are known in the preliminary design stage, i.e.

- the numerical parameters of ship $\overline{x} \equiv (L, B, H, T, C_B, ...)$ which describe : main dimensions, hull form, coefficients, structural material properties
- the qualitative atributes $\overline{q} \equiv (K, R, p_1, ..., p_n)$ which identify vessel's functional type, class and topological features of hull structure
- the strength requirements of classification rules ;

into estimated values of the hull mass M and its gravity centre height, Zg :

$$M = F(\overline{x}, \overline{q}) \quad \text{and} \quad Zg = F(\overline{x}, \overline{q}) \tag{1}$$

A practical aspect of this work is to get a parametric method easily codable into a computer program – useful for the estimating of the mass and gravity centre height of inland waterways vessels in the preliminary design stage. The cognitive aspect of the work is to investigate and broaden theoretical knowledge on the relationships between parameters of inland waterways vessels and their mass characteristics.

The research in question has resulted from practical needs which have arisen during studies on the INCOWATRANS E!3065 (Inland and Costal Water Transport System) Project carried out within the frame of the UE EUREKA Program aimed at development of a modern, ecological friendly fleet of inland waterways vessels.

RESEARCH PROGRAM AND ITS ASSUMPTIONS

By making use of relevant knowledge dealing with sea-going ships, given in [5,15] the hull parameters *a priori* assumed to be significantly affecting its mass characteristics, were preliminarily selected. Hull mass magnitude depends on both – vessel's numerical parameters and its qualitative features. Some assumptions simplifying real relationships were introduced to determine simple mathematical models – describing in an approximate way the problem in question. It was assumed that for purposes of approximate estimation of vessel's mass its hull can be identified enough correctly by the following items :

two functional types of vessel :
dry cargo vessels
liquid cargo vessels

vessel's class
defined by permissible region of navigation

vessel's main particulars :
L - length
B - breadth
H - depth to upper deck
T - design draught
C_B - hull block coefficient

other parameters :
k - permissible stress coefficient
Re - yield strength of structural steel.

The hull structure scantlings of dry cargo vessels and liquid cargo ones are determined in a different way – therefore the following structural elements are taken into account [13] :

for dry cargo vessels :
- hatch openings in decks
- hatch coamings
- specific features of double bottom

for liquid cargo vessels :
- longitudinal bulkheads
- continuous structure of decks
- specific features of double bottom.

Variability ranges of the hull parameters of investigated hull series were determined on the basis of the data from literature [10, 17, 18]. Calculations for hull series covered all combinations of the following items :

- functional types of liquid and dry cargo vessels
- PRS (Polish Register of Shipping) ship classes concerning the restricted navigation regions R : 1, 2, 3
- values of the length L : 25.00 m, 50.00 m, 75.00 m and 100.00 m
- values of the breadth B – resulting from the assumed ratio of L/B : 4, 5, 6
- values of the depth H resulting from the assumed ratio of L/H : 10, 15, 20
- values of the draught T resulting from the assumed ratio of H/T : 1.25, 1.5, 2.0.

Moreover, the following constant parameters were assumed :

- values of the block coefficient C_B : 0.7, 0.8, 0.9
- normal strength (NW) steel of 235 MPa yield strength
- permissible stress coefficient k = 0.7.

The number of hull variants I_w of the hull series is equal to product of variants of values of varying parameters, i.e. : vessel class, length, breadth, depth, draught and block coefficient, namely I_w = 972 variants of hulls of any considered vessel functional type.

Simulating calculations were performed by using the elaborated computer program INLAND_VESSEL_HULL_ _MASS.PAS [14] which realizes the algorithm for determining hull scantlings of inland waterways vessels [13]. Results of the calculations are presented in the report [14].

MODELING VESSEL'S MASS CHARACTERISTICS

An analytical relationship expressing the relation between mass of hull and its main design parameters should have the following features :

- accuracy – to correctly approximate a statistical sample
- simplicity – mathematical model should be convenient for design calculations and computer programming
- good estimating properties – to provide credible predictions.

It is not an easy task to satisfy the above mentioned requirements because of multi-dimensionality and nonlinear character of the analyzed relationships. To find the relations the least square approximation method was applied, and by means of the iterative procedures :

- hypotheses on approximation relationships were stated
- structural parameters of approximation model were determined
- preliminary tests were performed
- approximation hypotheses were verified by assessing measures of accuracy.

To obtain sufficient accuracy a special normalizing technique was applied, similar to that given in [15]. The procedure consisted in preliminary choice of the normalizing function $g(\overline{x})$ monotonically compatible with the approximated function $F(\overline{x})$ – representing discrete values of simulated masses of hull series , and in determining the normalized smooth function $w(\overline{x})$ (of small variations) :

$$\frac{F(\overline{x})}{g(\overline{x})} = w(\overline{x}) \qquad \overline{x} \in \Omega \tag{2}$$

Next, the function $a(\overline{x})$ approximating the normalized function $w(\overline{x})$ is determined. If the determined function $a(\overline{x})$ correctly approximates the function $w(\overline{x})$, then the function $f(\overline{x})$:

$$f(\overline{x}) = g(\overline{x}) \cdot a(\overline{x}) \tag{3}$$

correctly approximates the function $F(\overline{x})$, hence this is the searched for solution of the problem in question.

In the case of modelling hull mass characteristics a normalizing function may be e.g. either the product of vessel main dimensions (modular function) :

$$g(\overline{x}) = L \cdot B \cdot H \tag{4}$$

or the power function :

$$g(\overline{x}) = c \cdot \prod_{i=0}^{n} x_i^{a_i} = c \cdot L^{a1} \cdot B^{a2} \cdot H^{a3} \cdot T^{a4} \cdot C_B{}^{a5} \cdot R^{a6} \quad (5)$$

The proper selection of a normalizing function is important in order to get sufficient accuracy of hull mass characteristics approximation.

APPROXIMATED HULL MASS CHARACTERISTICS

Final results of the best parametric models for mass characteristics are below presented in the tables containing the following items :

- hypothesis on a form of normalizing function
- hypothesis on a form of approximating function with a list of variable parameters (great-letter symbols) and structural constants of the model (small-letter symbols)
- estimated values of structural constants of the mathematical model
- correlation indices for assessing significance of design parameters
- estimated values of approximation accuracy measures, where :
  - E-average [%] – relative percentage error of approximation
  - E-max [%] – maximum relative percentage error of approximation for the whole sample
  - E > x% [%] – percentage of relative errors exceeding x% in the whole sample (of 972 elements).

The requirement for model simplicity was fulfilled by applying the power function formulas only – useful in calculating values of the function derivatives – a feature convenient for linearization of a mathematical model of a design problem.

Hull structure mass estimation

Significance of the influence of vessel parameters on hull structure mass was assessed by means of the determined coefficients of correlation, then non-significant parameters – of small correlation coefficient values – were eliminated from the approximation model. In the case of liquid cargo vessels the obtained best approximation formula is given in Tab.1

Tab. 1. *Structure, constants and accuracy of the approximation formula for hull mass estimation*

Liquid cargo inland vessels – sample of 972 simulated hulls

Approximation hypothesis : $g(\overline{x}) = L \cdot B \cdot H$

$$M_H(\overline{x}) = g(\overline{x}) \cdot f(\overline{x}) = c \cdot L^{cl} \cdot B^{cb} \cdot H^{ch} \cdot T^{ct} \cdot C_B{}^{cc} \cdot R^{cr}$$

Hypothesis verification

Determined values of structural parameters

c	0.0631615	**cl**	1.43625	**cb**	0.973853	**ch**	-0.190530
ct	0.150033	**cc**	0.154456	**cr**	-0.264760		

Correlation coefficients

Variables	**L**	**B**	**H**	**T**	C_B	**R**
M_H	0.923	0.938	0.757	0.718	0.017	-0.137

Approximation accuracy measures

E-average [%]	**E-max** [%]	**E > 10%** [%]
3.40	10.08	0.10

In the case of dry cargo vessels the best approximation was obtained by the formula whose description and accuracy assessment is given in Tab.2.

Tab. 2. *Structure, constants and accuracy of the approximation formula for hull mass estimation*

Dry cargo inland vessels – sample of 972 simulated hulls

Approximation hypothesis : $g(\overline{x}) = L \cdot B \cdot H$

$$M_H(\overline{x}) = g(\overline{x}) \cdot (f_1(\overline{x}) + f_2(\overline{x})) = F_1(\overline{x}) + F_2(\overline{x})$$

$$F_1(\overline{x}) = c \cdot L^{cl} \cdot B^{cb} \cdot H^{ch} \cdot T^{ct} \cdot C_B{}^{cc} \cdot R^{cr}$$

$$F_2(\overline{x}) = s \cdot L^{sl} \cdot B^{sb} \cdot H^{sh} \cdot T^{st} \cdot R^{sr}$$

Hypothesis verification

Determined values of structural parameters

c	0.061267634	**cl**	1.701378	**cb**	0.404710	**ch**	0.0183751
ct	0.179208	**cc**	0.163863	**cr**	-0.242087		
s	0.000045058	**sl**	2.06496	**sb**	1.31413	**sh**	1.424301
st	-0.42505	**sc**	----	**sr**	-0.32789		

Correlation coefficients

Variables	**L**	**B**	**H**	**T**	C_B	**R**
M_H	0.921	0.897	0.835	0.784	0.006	-0.127

Approximation accuracy measures

E-average [%]	**E-max** [%]	**E > 10%** [%]
3.40	10.08	0.10

Estimation of height of hull structure gravity centre

No correlation was revealed between the gravity centre height and the hull block coefficient C_B as well as the navigation region R – both for dry cargo and liquid cargo vessels.

The best approximation model found for the gravity centre height of liquid cargo vessels, $Zg = f(\overline{x})$, is presented in Tab.3 and in the case of dry cargo vessels – in Tab.4.

Tab. 3. *Structure, constants and accuracy of the approximation formula for hull gravity centre height*

Liquid cargo inland vessels – sample of 972 simulated hulls

Approximation hypothesis : $g(\overline{x}) = H$

$$Zg(\overline{x}) = g(\overline{x}) \cdot f(\overline{x}) = c \cdot L^{cl} \cdot B^{cb} \cdot H^{ch} \cdot T^{ct}$$

Hypothesis verification

Determined values of structural parameters

c	0.46023	**cl**	0.02939	**cb**	1.781E-5	**ch**	0.9250	**ct**	2.753E-5

Correlation coefficients

Variables	**L**	**B**	**H**	**T**	C_B	**R**
Z_g	0.826	0.765	1.000	0.932	0.000	0.000

Approximation accuracy measures

E-average [%]	**E-max** [%]	**E > 5%** [%]
0.69	1.59	0.00

Tab. 4. *Structure, constants and accuracy of the approximation formula for hull gravity centre height*

Dry cargo inland vessels – sample of 972 simulated hulls

Approximation hypothesis : $g(\overline{x}) = H$

$$Zg(\overline{x}) = g(\overline{x}) \cdot f(\overline{x}) = c \cdot L^{cl} \cdot B^{cb} \cdot H^{ch} \cdot T^{ct}$$

Hypothesis verification

Determined values of structural parameters

c	0.40144	**cl**	0.09297	**cb**	-1.960E-5	**ch**	0.7177	**ct**	0.000307

Correlation coefficients

Variables	**L**	**B**	**H**	**T**	C_B	**R**
Z_g	0.843	0.781	0.998	0.930	0.000	0.000

Approximation accuracy measures

E-average [%]	**E-max** [%]	**E > 5%** [%]
1.64	3.19	0.00

POWER PLANT MASS AND OUTFIT MASS CHARACTERISTICS

Estimation of mass of medium and high-speed marine diesel engines

Ship power plant mass essentially depends on a type of engines of the propulsion system. On inland waterways vessels, are commonly installed medium-speed diesel engines (of 500÷600 rpm) and high-speed ones (of 1500÷1800 rpm), which transfer power either directly, or through mechanical, hydraulic or electrical transmission gear – to the screw propeller(s) of fixed or controllable pitch, often accommodated in a Kort nozzle.

Diesel engine mass depends on its rated torque, power output, cylinder arrangement and its supercharging. Apart from the engine itself, mass of power plant consists of masses of its equipment and systems. Data contained in the subject-matter literature usually concern ship power plants with the engines of low speed – applicable to sea-going ships; e.g. in [1] is given a formula for determining mass of ship diesel engines of low and medium speed – of more than 1000 kW rated power :

$$M_{EN} = 12\left(\frac{P}{n}\right)^{0.84} \quad [t] \qquad (6)$$

where :
P - installed engine power [kW]
n - engine speed [rpm].

Publications dealing with vessel power plants equipped with medium-speed and high-speed diesel engines of relatively small power are scarce.

For purposes of the INCOWATRANS design study on inland waterways passenger vessel, a research work on mass of medium-speed and high-speed engines of small power was performed on the basis of the catalogue data of: Volvo-Penta, Deutz, MAN, Caterpillar, Detroit Diesel, Wola-Henschel and Wärtsilä. The collected data of the engine parameters and its mass values were used as a statistical sample to determine an analytical relationship approximating mass of medium-speed and high-speed marine diesel engines of small power. In result, the following simple formula was obtained :

$$M_{EN} = 7130 \cdot \frac{P^{0.85}}{n^{1.75}} \quad [t] \qquad (7)$$

where :
P - installed engine power [kW]
n - engine speed [rpm]

A comparison of the unit mass of the engines :

$$m_e = \frac{M_{EN}}{P} \quad [kg/kW]$$

calculated by the formula (6) – dashed lines (engines for sea-going ships), and (7) – continuous lines (engines for inland waterways vessels) is presented on Fig.1.

From the comparison it results that in the case of medium-speed engines (of 750 rpm) the engine mass according to (7) is greater by about 60% than that estimated by using (6). For the high-speed engines (of 2500 rpm) the mass according to (7) is smaller by about 50% that that estimated by means of (6). For the engines of speeds within the range of 1000÷2000 rpm so estimated values of mass are similar.

Estimation of mass of power plants fitted with medium and high-speed engines

Power plant mass of sea-going ships without stores („dry weight" condition) acc. [1] can be determined as a sum of mass of the main engine and mass of the remaining elements of the power plant :

$$M_R = k_R \cdot P^{0.7} \quad [t] \qquad (8)$$

where : k_r - a coefficient taking values from the interval of 0.19 ÷ 0.83 - depending on a ship functional type.

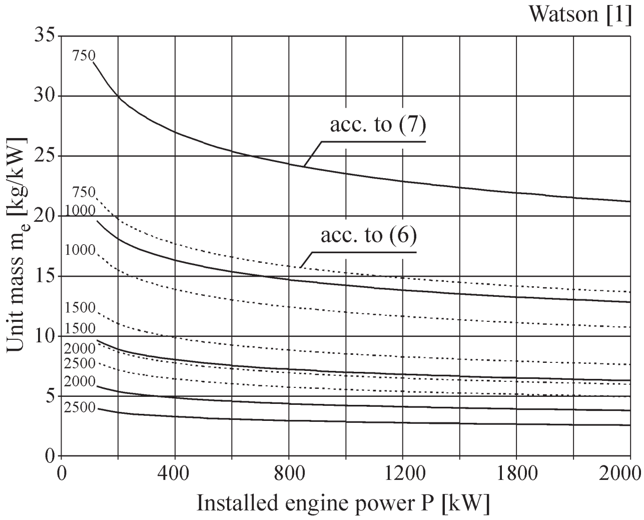

Fig. 1. *Comparison of the values of the unit mass of ship medium- and high-speed diesel engines, obtained from the formula (6) (dashed lines) and (7) (continuous lines)*

Main engine mass of inland waterways vessels reaches about 30% ÷ 45% of the total mass of the power plant (in "dry weight" condition). To determine mass of a vessel power plant fitted with medium-speed or high-speed engines the following formula was elaborated :

$$M_P = 7130 \cdot \frac{P^{0.85}}{n^{1.75}} + k_R \cdot P^{0.7} \quad [t] \qquad (9)$$

Fig.2. presents a comparison of the unit mass of power plants

$$m_p = \frac{M_P}{P} \quad [kg/kW]$$

calculated by means of the formula (6) and (8) – dashed lines, and formula (9) – continuous lines – in both cases $k_R = 0.2$

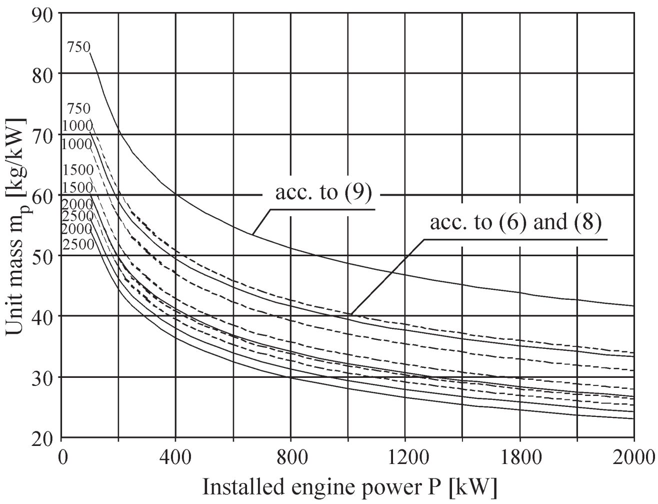

Fig. 2. *Comparison of the unit mass of ship power plants with medium- and high-speed diesel engines, obtained from the formula (6 and 8) – dashed lines, and formula (9) – continuous line*

In the case of power plant of high-speed engines it is often necessary to apply a reduction gear. To estimate mass of a mechanical reduction gear the following formula was elaborated :

$$M_G = 4 \cdot \frac{P}{n} \quad [t] \qquad (10)$$

Estimation of hull outfit mass

Mass characteristics of hull outfit are not easily modeled mathematically as they depend not only on numerical parameters of a ship but also on such factors as: ship functional type, outfitting standard, crew number, as well as on obligatory requirements of relevant provisions of maritime administration and a society classification rules. Within the frame of the INCOWATRANS project no such research work was made. But on the basis of the diagrams given in [7] the following approximating analytical formula concerning inland waterways vessels, useful in the preliminary design stage, were elaborated :

hull equipment mass :

$$M_E = 0.125 \cdot (L \cdot B \cdot H)^{2/3} \quad [t] \qquad (11)$$

mass of hull systems :

$$M_S = 0.25 \cdot \left(L \cdot B \cdot H\right)^{1/2} \quad [t] \qquad (12)$$

hull outfit mass :

$$M_O = 0.025 \cdot \left(L \cdot B \cdot H\right)^{2/3} \quad [t] \qquad (13)$$

where all dimensions are in [m].

PRELIMINARY ASSESSMENT OF THE METHOD'S PREDICTING CAPABILITY

An attempt to preliminarily assess predicting capability of the method in question was made by taking into account, as an example, several vessels whose data were obtained from their PRS class documentation. In the case of the SINE 207 inland waterways container vessel of 18/36 TEU capacity its preliminary design documentation was used. Results of the verifying calculations are presented in Tab.5.

SUMMARY

- The scantling determination algorithm used to elaborate the presented parametric method concerns the inland waterways vessels intended for the carrying of general cargo and dry and liquid bulk cargoes.
- The performed verification of the method showed that in the case of the passenger vessels and container vessels the achieved predictions of :
  - ★ mass characteristics – are acceptable approximations for purposes of the preliminary design stage (mean error is of about 15%)
  - ★ gravity centre height characteristics – are acceptable approximations for purpopses of the preliminary design stage (mean error is less than 14%)
- In the case of the vessels of a different structure, e.g. car ferries – intended for the carrying roll-on – roll-off cargoes, fitted with heavy decks (M/V Berlin, M/V Bielik II), the obtained results are different from the values summed up of detail mass specifications.
- For light cargo vessels the proposed parametric method of mass prediction can be a useful tool in preliminary design stage.

NOMENCLATURE

B - breadth
C_B - block coefficient
E - relative percentage error
$f(\overline{x})$ - approximating function of hull mass and its gravity centre
$F(\overline{x})$ - approximated function of hull mass and its gravity centre height
$g(\overline{x})$ - normalizing function
H - depth
L - length
m_e - unit mass of engine
m_p - unit mass of power plant
M_E - hull equipment mass
M_H - hull mass
M_L - real vessel mass

Tab. 5. *Results of verifying calculations to assess predicting capability of the presented method*

Parameters		Vessel name and functional type						
Symbol	Unit	SINE207 *Container*	Berlin *Car ferry*	Arno II *Passenger*	Bielik II *Car ferry*	Bełdany *Passenger*	Perkoz *Passenger*	Posejdon *Passenger*
L	[m]	56.5	51.85	33.58	47.51	33.56	21.4	21.16
B	[m]	9	12.72	6.2	15.59	6.1	4.12	4.23
H	[m]	3.00	6.80	2.96	6.40	2.90	1.5	1.20
T	[m]	1.6	2.74	1.5	2.25	0.94	0.7	0.65
C_B	[-]	0.9	0.55	0.46	0.7	0.6	0.6	0.6
R	[-]	3	3	2	3	3	3	3
P	[kW]	620	820	300	1000	160	70	110
n	[rpm]	1500	500	500	1500	500	1500	1500
M_H	[t]	128.5	153.1	42.6	135.1	36.2	13.5	13.1
M_P	[t]	22.7	62.3	28.0	32.2	17.1	4.6	6.4
M_E	[t]	16.6	34.0	7.6	28.3	5.8	3.2	2.8
M_S	[t]	9.8	16.7	5.4	14.6	4.5	2.9	2.6
M_O	[t]	3.3	6.8	1.5	5.7	1.2	0.6	0.6
M_{LP}	[t]	180.8	273.0	85.2	240.1	71.7	24.9	25.5
M_L	[t]	144.5	734.5	98.7	657.8	85	23.4	20.2
E_M	[%]	20	63	10	64	16	6	21
Z_{gr}	[m]	1.78	4.27	2.10	3.79	2.00	1.07	0.90
Z_g	[m]	1.95	4.08	2.49	3.73	1.83	1.01	1.28
E_Z	[%]	9	5	16	2	8	6	30

M_{LP} - predicted mass of vessel
M_O - hull outfit mass
M_P - power plant mass
M_S - mass of hull systems
n - engine speed
NW - normal strength steel acc. PRS
P - installed (rated) engine power
$\bar{q}$ - vector of qualitative design attributes of vessel
R - permissible region of navigation
T - draught
$\bar{x}$ - vector of numerical design parameters of vessel
Z_g - predicted height of vessel's gravity centre
Z_{gr} - real height of vessel's gravity centre
Ω - set of acceptable parameters.

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CONTACT WITH THE AUTHOR

Jan P. Michalski, Assoc.Prof.
Faculty of Ocean Engineering
and Ship Technology,
Gdańsk University of Technology
Narutowicza 11/12
80-952 Gdańsk, POLAND
e-mail : janmi@pg.gda.pl

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Shanghai Jiao Tong University

Ship Stability Workshop

After the preceding workshops of the kind held in Great Britain, Japan, Greece, Canada, Italy and USA, the 7th International Ship Stability Workshop was organized in China. The interesting scientific meeting of naval architects was held on 1÷3 November 2004 in Shanghai Jiao Tong University.

Its program contained 28 papers presented during the following sessions :

- Theoretical Development in Damage Stability
- Damage Survivability Assessment
- Assessment of Ship Stability Safety
- Theoretical Prediction of Intact Stability
- Experimental Investigation of Intact Stability
- Ship Dynamics with Water on Deck and Extreme Waves
- Stability Research in China

Authors of the papers represented scientific centres of Canada, China, Finland, Germany, Greece, Holland, Italy, Japan, Sweden, United Kingdom and USA.

Among them it was Prof. M.Pawłowski from Gdańsk University of Technology, Poland, who took part in the activity of International Standing Committee, and – during 2nd session – presented the paper titled :

General framework of new subdivision regulations

Photo : Beata Gis