A method for predicting propeller-hull interaction, applicable to preliminary design of inland waterways ships

Jan P. Michalski, Assoc. Prof.
Gdańsk University of Technology
Polish Naval University

ABSTRACT

This paper presents a proposal of a parametric method for predicting the characteristics of wake fraction, $w(\bar{x})$, and thrust deduction, $t(\bar{x})$, of ship hull of the draught close to waterway depth. The method makes it possible to take into account an influence of low waterway depth in preliminary selecting propulsion system parameters of ships intended for operating in shallow waters, e.g. of inland waterways ships. The mathematical model of the problem was determined with taking into account the aspect of coding easiness of calculation algorithm to be applied to computer software useful in computer aided design. Application of the method was demonstrated with the use of the example characteristics of the passenger ship intended for operating in shallow waters on Berlin-Kaliningrad route, whose design was elaborated in the frame of the EU Eureka INCOWATRANS E!3065 project.

Keywords : design of inland waterways ships, selection of propulsion system parameters, characteristics of propeller – hull interaction.

AIM AND SCOPE OF THE WORK

In the classical problems of ship design theory, mutual interaction of ship hull and a propeller operating close to ship stern, is expressed by characteristics of the wake fraction w and the thrust deduction t, dependent on the vector of ship parameters $\bar{x} = (x_1, x_2, x_3, \ldots)$, such as hull main dimensions, its form coefficients etc. The relations found in literature sources, used to practically determine the characteristics $w(\bar{x})$ and $t(\bar{x})$, are given in the form of diagrams or non-structural formulae based on approximation of large number of data obtained from experimental model tests. In the problems of ship theory it is assumed that for a given ship hull, values of w and t functions are constant; for this reason in the subject-matter literature the characteristics are usually called "interaction coefficients (factors)". In the problems of ship design theory, w and t should be considered as functions of the arguments $\bar{x} = (x_1, x_2, x_3, \ldots)$, i.e. as the hull influence characteristics.

In the case of sea-going ships operating in practically unlimited waters, the reliable characteristics $w(\bar{x})$and $t(\bar{x})$ can be achieved by using the known methods, e.g. that of Holtrop and Mennen [1] or that of Harvald [2].

If the characteristics $w(\bar{x})$ and $t(\bar{x})$ are additionally made dependent on waterway's parameters and ship speed then generalized characteristics useful for the designing of propulsion systems of ships intended for operating in shallow waters, can be obtained. Lack of such generalized methods is a shortage in engineering knowledge and an obstacle in defining correct methods for selecting propulsion system parameters of inland navigation ships. The necessity of overcoming the drawbacks, resulting from practical design needs, has constituted an inspiration to undertake the investigations in question.

The characteristics $w(\bar{x})$ and $t(\bar{x})$represent total energy balance which takes place in the water flow around hull – they result from the phenomena associated with boundary layer forming, wave system generating as well as influence of water area limits on flow velocity field [2, 3, 4].

Empirical investigations concerning the influence of water area limitations, i.e. its depth and width, on hydrodynamic characteristics of hull-propeller interaction, meet difficulties both of conceptual and measuring nature since an influence of particular factors is difficult to be identified and generalized, moreover physical quantities to be determined in such experiments are hardly measurable. Hence the scarce subject-matter literature provides not many experimental results though such knowledge is crucial for engineering applications. To have at one's disposal the generalized characteristics is necessary for determining correct, especially optimum, values of propulsion system parameters of the ship adjusted to operation in restricted waters. Correct choice of propulsion system greatly influences service and economic merits of designed ship - hence it may have a great impact onto ship owner's investment decisions.

In order to elaborate a computer method for optimum selection of propulsion system parameters of the ship intended for operating in shallow waters it is necessary to have at one's disposal a set of parametric mathematical models, namely :

- ❖ the hull resistance characteristics $R(\bar{x})$ – taking into account that the resistance depends also on the considered waterway's depth and width, as given in [5]
- ❖ the characteristics of wake fraction, $w(\bar{x})$, and thrust deduction, $t(\bar{x})$, including their dependence also on waterway depth and width (to be presented)
- ❖ the hydrodynamic characteristics, $K_T(\bar{x})$, $K_Q(\bar{x})$, of propellers, within a broad spectrum of their geometrical parameters.

In this paper is proposed a method for determining parametric mathematical models of the wake fraction, $w(\bar{x})$and thrust deduction, $t(\bar{x})$, including influence of ship speed and waterway depth. The mathematical models determined by means of the proposed method are unique, being a cognitive achievement and contributing to development of ship design theory. Usefulness of the method is demonstrated by the presented example of its application to the determining of the characteristics $w(\bar{x})$ and $t(\bar{x})$of the ship designed within the frame of the Eureka E!3065 INCOWATRANS project.

The planned application of the method concerns its use for optimization of propulsion system parameters for inland navigation ships intended for operating on shallow waterways.

INTRODUCTION

The propeller thrust horsepower N_T is as a rule greater than the towrope hull horsepower N_h, which is conditioned by the wake and thrust deduction interaction between propeller and hull's stern part. Propeller which operates near the hull and waterway bed, moves relative to water with the advance speed v_p , smaller than the ship speed v. The difference of the speeds :

$$\Delta v = v - v_p \tag{1}$$

determines the wake velocity, whereas the ratio :

$$w = \frac{\Delta v}{v} \tag{2}$$

defines the wake characteristics,
and the advance speed is then expressed as follows :

$$v_p = v(1 - w) \tag{3}$$

The wake speed depends both on the velocity field within the flow considered potential, and the boundary layer distribution on hull surface. The wake characteristics can be approximately expressed in the form of the sum of components as follows :

$$w = w_v + w_p \tag{4}$$

where :

w_v – stands for the viscosity component
w_p – the potential component which can be determined by means of theoretical methods of ideal fluid hydromechanics.
Hence for geometrically similar hulls the wake fraction is a function both the Froude number Fn and the Reynolds number Rn :

$$w_p = f(Fn) \;\; ; \;\; w_v = f(Rn) \;\; \rightarrow \;\; w = f(Fn, Rn) \tag{5}$$

Magnitude of the wake fraction depends on hull form – mainly on its fullness and slenderness. A large fullness and small slenderness make flow –around – stern velocity to drop significantly. At a small fullness and large slenderness the potential wake speed may be near zero, and in some circumstances – even of a negative value. In unlimited waters such case can happen when the behind-the-stern propeller finds itself in trough of ship-generated wave. The viscosity component depends on the boundary layer distribution over hull surface, which increases in function of square root of ship length up to the point of flow separation dependent on a form of stern part of ship's hull.

Propeller's work modifies the nominal pressure field in the stern region since an increase of water velocity resulting from the propeller work makes dynamic pressure dropping which generates the effect of thrust deduction increasing ship pressure resistance. The increase of flow velocity makes tangential stresses increasing in the stern part of hull, which results in viscosity resistance increasing. Hence the resistance of the propeller-driven ship is greater than that of the ship towed by an external force.

For a ship in uniform motion the thrust force T_p generated by its propeller is to be greater than the propulsion force T_N balancing the towed – ship resistance R :

$$T_p - \Delta T = T_N = R \tag{6}$$

where :

ΔT – increase of resistance due to decreased pressure in the stern region, resulting from propeller work.

By the ratio :

$$t = \frac{\Delta T}{T_p} \tag{7}$$

the thrust deduction fraction characteristics is defined [6, 7].

Selection of ship propulsion system parameters is performed under assumption that the state of kinematic equilibrium which occurs at the equality of forces, is achieved :

$$T_p = \frac{R}{1 - t} \tag{8}$$

The fraction t depends also on the Froude number and Reynolds number.
Reducing the problem to an ideal, one can express the thrust deduction fraction as the sum of components as follows :

$$t(Fn, Rn) = t_p(Fn) + t_v(Rn) \tag{9}$$

The propeller thrust power N_T is the product of the thrust force and the propeller speed respective to water :

$$N_T = T_p \cdot v_p \tag{10}$$

In the subject-matter literature the ratio of the hull towrope horsepower N_h and the propeller thrust power N_T , marked ξ_k , is called – the hull efficiency, or more correctly – the hull interaction factor :

$$\frac{N_h}{N_T} = \xi_k = \frac{1 - t}{1 - w} \tag{11}$$

The hull interaction factor does not comply with the definition of efficiency since the $w(\bar{x})$expresses a return of a part of the energy earlier delivered by propulsion system to the water surrounding the hull, and $t(\bar{x})$ - a loss of the power resulting from the suction effect exerted by propeller onto hull. When the quantity $w(\bar{x})$ is greater than the quantity $t(\bar{x})$, then ξ_k is greater than 1, that can be obtained in the case when the hull stern form is designed correctly.

The conventional character of the hull interaction factor is usually distinguished by attributing to it the symbol ξ instead of η traditionally standing for efficiency.

CONCEPT OF THE METHOD AND ITS ASSUMPTIONS

Basin [7] – on the ground of his own experiments as well as some literature data – presented the diagrams of $w(\bar{x})$ and $t(\bar{x})$characteristics for inland navigation ships of typical hull form, making the following quantities variable :

- the ratio h/T > 1, i.e. that of the water depth h and the ship draught T
- the Froude number related to the water depth $F_h \frac{v}{\sqrt{g_z \cdot h}}$
- location of the hull buoyancy centre.

The diagrams presented in [7] concern only that hull whose parameters were assumed the same as of the parent hull form. However the diagrams are rather not useful for elaborating computer calculation algorithms – in contrast to relevant mathematical models. Moreover, in order to elaborate a design method it is necessary to generalize the diagrams [7] in such a way as to cover the hulls of extrapolated parameters. Further considerations are focused on realization of the postulates.

To this end, were prepared the tables of discrete values taken from the diagrams [7], which next served as the basis for determination of approximate analytical relationships.

The analytical relationships to be determined, should be so chosen as to correctly approximate the set of discrete values of the characteristics $\{w_i(\bar{x})\}$ and $\{t(\bar{x})\}$ for various hull form parameters $\bar{k}$, Froude numbers F_h, and ratios h/T. The following analytical relationships were postulated :

$$w(\bar{x}) = w\left(F_h, \frac{h}{T}, \bar{k}\right) \tag{12}$$

$$t(\bar{x}) = t\left(F_h, \frac{h}{T}, \bar{k}\right) \tag{13}$$

To make further description of the formulae easier the following notations were applied : F_h = p and h/T = g.

A hypothetical structure of mathematical models of the determined characteristics was *a priori* assumed in the form of the product of functions having identical structure, and being the combinations of elementary analytical functions as follows :

$$w(p, g, \bar{k}) = F(p, g) \cdot r(\bar{k}) \tag{14}$$

$$t(p, g, \bar{k}) = F(p, g) \cdot s(\bar{k}) \tag{15}$$

The functions dependent on full form parameters, $r(\bar{k})$and $s(\bar{k})$, deal with the characteristics concerning deep water conditions - for the designed hull and parent hull, respectively, and the function f(p, g) has to take into account the influence of ship speed and waterway depth.

SELECTION OF STRUCTURE OF MATHEMATICAL MODELS

Within the frame of the established structure of approximating models, different combinations of elementary analytical functions were tested by determining numerical values of approximation accuracy measures, and on this basis the most appropriate model was chosen. Both in the case of the wake fraction and thrust deduction characteristics the best approximation, at h/T = const and H_h = var, was achieved by applying the rational function which makes it possible to obtain a required number of inflection points :

$$f(p, g_j = \text{const}) = \frac{\sum_{i=0}^{3} c_i \cdot p^i}{\sum_{i=4}^{7} c_i \cdot p^i} = \tag{16}$$

$$= \frac{c_{0,j} + c_{1,j} \cdot p^1 + c_{2,j} \cdot p^2 + c_{3,j} \cdot p^3}{c_{4,j} + c_{5,j} \cdot p^1 + c_{6,j} \cdot p^2 + c_{7,j} \cdot p^3}$$

The constants $c_{i,j}$ appearing in the formula (16) in the case of the characteristics $w(\bar{x})$, are presented in Tab.1, and the constants dealing with the characteristics $t(\bar{x})$ – in Tab.2.

***Tab. 1.** Values of the coefficients $c_{i,j}$ for determination of the characteristics $w(\bar{x})$.*

Coefficients $c_{i,j}$ in $f(p, g_1)$		Coefficients $c_{i,j}$ in $f(p, g_2)$		Coefficients $c_{i,j}$ in $f(p, g_3)$	
$C_{0,1}$	3.75903	$C_{0,2}$	-0.79985	$C_{0,3}$	0.30069
$C_{1,1}$	-13.42912	$C_{1,2}$	3.63016	$C_{1,3}$	-0.51936
$C_{2,1}$	16.01725	$C_{2,2}$	-5.02485	$C_{2,3}$	0.29658
$C_{3,1}$	-6.38144	$C_{3,2}$	2.18602	$C_{3,3}$	0.0
$C_{4,1}$	21.09661	$C_{4,2}$	-8.77254	$C_{4,3}$	2.32048
$C_{5,1}$	-74.00941	$C_{5,2}$	40.91477	$C_{5,3}$	-4.86127
$C_{6,1}$	86.11529	$C_{6,2}$	-60.43182	$C_{6,3}$	3.14136
$C_{7,1}$	-33.20242	$C_{7,2}$	28.81875	$C_{7,3}$	0.0

***Tab. 2.** Values of the coefficients $c_{i,j}$ for determination of the characteristics $t(\bar{x})$.*

Coefficients $c_{i,j}$ in $f(p, g_1)$		Coefficients $c_{i,j}$ in $f(p, g_2)$		Coefficients $c_{i,j}$ in $f(p, g_3)$	
$C_{0,1}$	4.94207	$C_{0,2}$	-0.06528	$C_{0,3}$	0.24071
$C_{1,1}$	-6.49645	$C_{1,2}$	0.42923	$C_{1,3}$	-0.54335
$C_{2,1}$	-6.58369	$C_{2,2}$	-0.73321	$C_{2,3}$	0.34214
$C_{3,1}$	8.77740	$C_{3,2}$	0.37536	$C_{3,3}$	0.0
$C_{4,1}$	33.52143	$C_{4,2}$	-0.51611	$C_{4,3}$	3.41621
$C_{5,1}$	-44.26194	$C_{5,2}$	3.60430	$C_{5,3}$	-7.35229
$C_{6,1}$	-45.02972	$C_{6,2}$	-6.30664	$C_{6,3}$	4.13618
$C_{7,1}$	60.08500	$C_{7,2}$	3.27293	$C_{7,3}$	0.0

The constants were determined by applying the approximation method consisting in minimization of sum of squares of deviations over discrete set.

For the case of h/T = var and F_h = const a sufficient approximation accuracy was obtained by applying the Lagrange polynomial L_i having constant interpolation nodes as follows: h/T = g_1 = 2.0 ; h/T = g_2 = 4.0 and h/T = g_3 = 8.0, which cover the range of dimensionless waterway depth in question. As a result, the following structure of the formula was obtained:

$$\begin{aligned} F(p,g) &= \sum_{i=1}^{3} [L_i(g) \cdot f(p, g_i)] = \\ &= \frac{(g-g_2)\cdot(g-g_3)}{(g_1-g_2)\cdot(g_1-g_3)} \cdot f(p,g_1) + \\ &+ \frac{(g-g_1)\cdot(g-g_3)}{(g_2-g_1)\cdot(g_2-g_3)} \cdot f(p,g_2) + \\ &+ \frac{(g-g_1)\cdot(g-g_2)}{(g_3-g_1)\cdot(g_3-g_2)} \cdot f(p,g_3) \end{aligned} \tag{17}$$

In the method in question the influence of buoyancy centre location was not taken into account both due to a weak correlation with the determined characteristics and necessity of adjusting the method to be capable of identifying the ship in the preliminary design phase.

METHOD FOR DETERMINING GENERALIZED CHARACTERISTICS

The diagrams given in [7] concern the hull of the following parameters $\bar{k}_p = (L_p , B_p , T_p , CB_p , CM_p)$ = (80.0 m, 8.89 m, 1.25 m, 0.587, 0.981), which is considered as that of the parent form. At small F_h numbers the shallow water influence is low and the characteristics $w(\bar{x})$ and $t(\bar{x})$ are almost constant hence they can be determined with the use of the formulae valid for deep water. Hence the method of Holtrop and Mennen [1] was applied to determining w_m and t_m values both for the parent hull and designed one, respectively, which consequently served for determining the correction functions $r(\bar{k})$ and $s(\bar{k})$**,** namely :

$$r(\bar{k}) = \frac{w_m(\bar{k}_d)}{w_m(\bar{k}_p)} \tag{18}$$

$$s(\bar{k}) = \frac{t_m(\bar{k}_d)}{t_m(\bar{k}_p)} \tag{19}$$

where :

$w_m(\bar{k}_d)$ – deals with the designed hull and deep water
$w_m(\bar{k}_p)$ – the parent hull and deep water.

In the case of deep water the characteristics $w(\bar{x})$ and $t(\bar{x})$ are monotonous respective to the hull parameters $\bar{k}$, hence the characteristics described by the formulae (17) and corrected by the functions $r(\bar{k})$ and $s(\bar{k})$ in compliance with the formulae (14) and (15), model in an approximate way (extrapolate) the generalized characteristics $w(p, g, \bar{k})$ and $t(p, g, \bar{k})$, therefore they may serve for determining the characteristics of designed ship of variable parameters both of hull form, water depth and ship speed ; as they are expressed *explicite* by parametric mathematical models they satisfy the demand put to genuine parametric methods applicable to preliminary design of ships.

The generalized relationships can be next used for determining the generalized characteristics of propeller-hull interaction in shallow water, in compliance with the following formula :

$$\frac{N_h}{N_T} = \xi_k(p, g, \bar{k}) = \frac{1 - t(p, g, \bar{k})}{1 - w(p, g, \bar{k})} \tag{20}$$

The elaborated proposal of the method may be applicable to preliminary determining the parameters of propulsion system of ships intended for operating in shallow waters, e.g. in designing inland waterways ships.

In Fig.1 are graphically presented the characteristics of wake fraction, and in Fig.2 – those of thrust deduction, determined for the ship designed for the shallow waterway on Berlin–Kaliningrad route (the example concerns twin-propeller ship).

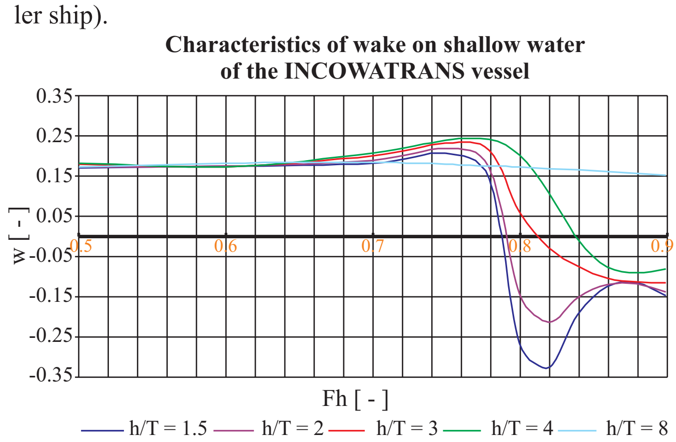

Fig. 1. *A graphic representation of the mathematical models of the wake fraction characteristics* $w(\bar{x})$ *for the INCOWATRANS ship .*

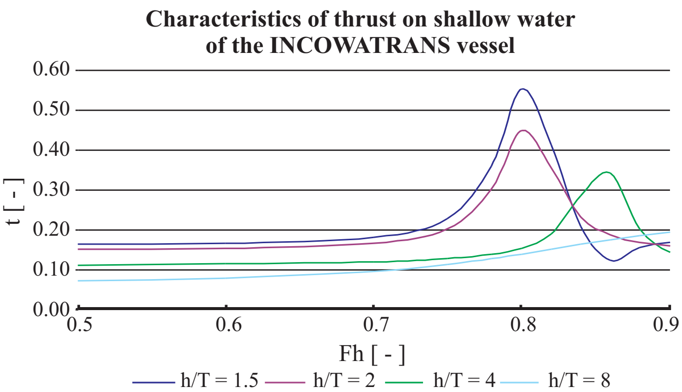

Fig. 2. *A graphic representation of the mathematical models of the thrust deduction characteristics* $t(\bar{x})$ *for the INCOWATRANS ship .*

SUMMARY

- The presented method can be used for determining the propeller-hull interaction characteristics in the case of designing a ship intended for operating in shallow waters of the depth only somewhat greater than ship's draught. The applied generalization makes it possible to approximately determine w and t characteristics in the cases not covered by the diagrams given in [7].
- Analysis of the presented models makes it possible to offer the following comments :
  - when the Froude number related to water depth decreases then the w function tends to the value corresponding with that for deep water (Fig.1)
  - when the Froude number exceeds the value of 0.7 then w value decreases
  - when the Froude number exceeds the value of 0.8 then, at a sufficiently large water depth, w value decreases only a little (bold line in Fig. 1)
  - when Froude number value is greater than $F_h = 0.75$ then the t characteristics increase up to their extreme value and next, in the case of shallow water, decrease (Fig.2).
- Recapitulating, when the value $F_h = 0.75$ is exceeded, then the smaller the water depth, the greater the drop of values of the hull interaction characteristics, which results in a drop of propulsion system efficiency.
- The determined models of the generalized characteristics $w(p, g, \bar{k})$ and $t(p, g, \bar{k})$ have been implemented in the computer algorithm under development, intended for the determining of optimum parameters of propulsion system for inland navigation ships.
- The presented conclusions are in compliance with the present empirical knowledge, however the presented quantitative assessment has been only possible on the basis of the elaborated mathematical models.
- Computer implementation of the presented method was used in design work concerning optimization of propulsion system parameters for the tourist passenger ship intended for operating on the inland waterway route between Berlin and Królewiec, designed within the frame of Eureka E!3065 INCOWATRANS project.
- The method can also find use in preliminary designing the propulsion systems for inland navigation ships intended for sailing on shallow rivers, canals and lakes, or for coastal ships and naval landing crafts.

NOMENCLATURE

g – dimensionless waterway depth
g_z – gravity acceleration
h – waterway depth
$\bar{k}$ – vector of hull form parameters
$\bar{k}_p$ – vector of parent hull form parameters
$\bar{k}_d$ – vector of designed hull form parameters
p – Froude number related to water depth
t – thrust deduction characteristics
t_m – thrust deduction characteristics for deep water
v – ship speed
v_p – velocity of water inflow to propeller
w – wake fraction characteristics
w_m – wake fraction characteristics for deep water
$\bar{x}$ – vector of ship parameters
B_p – parent ship breadth
C_{Bp} – parent ship hull block coefficient
C_{Mp} – parent ship hull midship-section coefficient
F_h – Froude number related to water depth
N_h – towrope horsepower
N_T – propeller thrust power
R – ship hull resistance
T – ship draught
T_N – propelling force
T_p – parent ship draught

T_P – propeller thrust

η – propeller efficiency

ξ_k – propeller –hull interaction characteristics.

BIBLIOGRAPHY

1. Holtrop J., Mennen G.G.J.: *An approximate power prediction method*. International Shipbuilding Progress. July, 1982
2. Buczkowski L., et al. : *Calculation* methods *for preliminary ship designing* (in Polish). (Set 2), Maritime Publishing House (Wydawnictwo Morskie). Gdańsk, 1976
3. Buczkowski L.: *Fundamentals of naval architecture, Part I*, (in Polish). Publishing House of Gdańsk University of Technology (Wydawnictwa Politechniki Gdańskiej). Gdańsk, 1970
4. Dudziak J.: *Ship theory* (in Polish). Maritime Publishing House (Wydawnictwo Morskie). Gdańsk, 1988
5. Michalski J.P: *Verification of preliminary predictions of resistance and elaboration of mathematical design characteristics of resistance of the InCoWaTranS ship* (in Polish). Research report No. 193/E/2005, Faculty of Ocean Engineering and Ship Technology, Gdańsk University of Technology. Gdańsk, 2005
6. Jarzyna H.: *Ship hull - propeller interaction* (in Polish). The Ossolińskis Scientific Establishment, Publishing House of Polish Academy of Sciences, 1993
7. Basin A.M., Wjelednickij I.O., Ljakowickij A.G.: *Gidrodinamika sudow na miełkowodie*. Izdatielstwo Sudostroienie, 1976

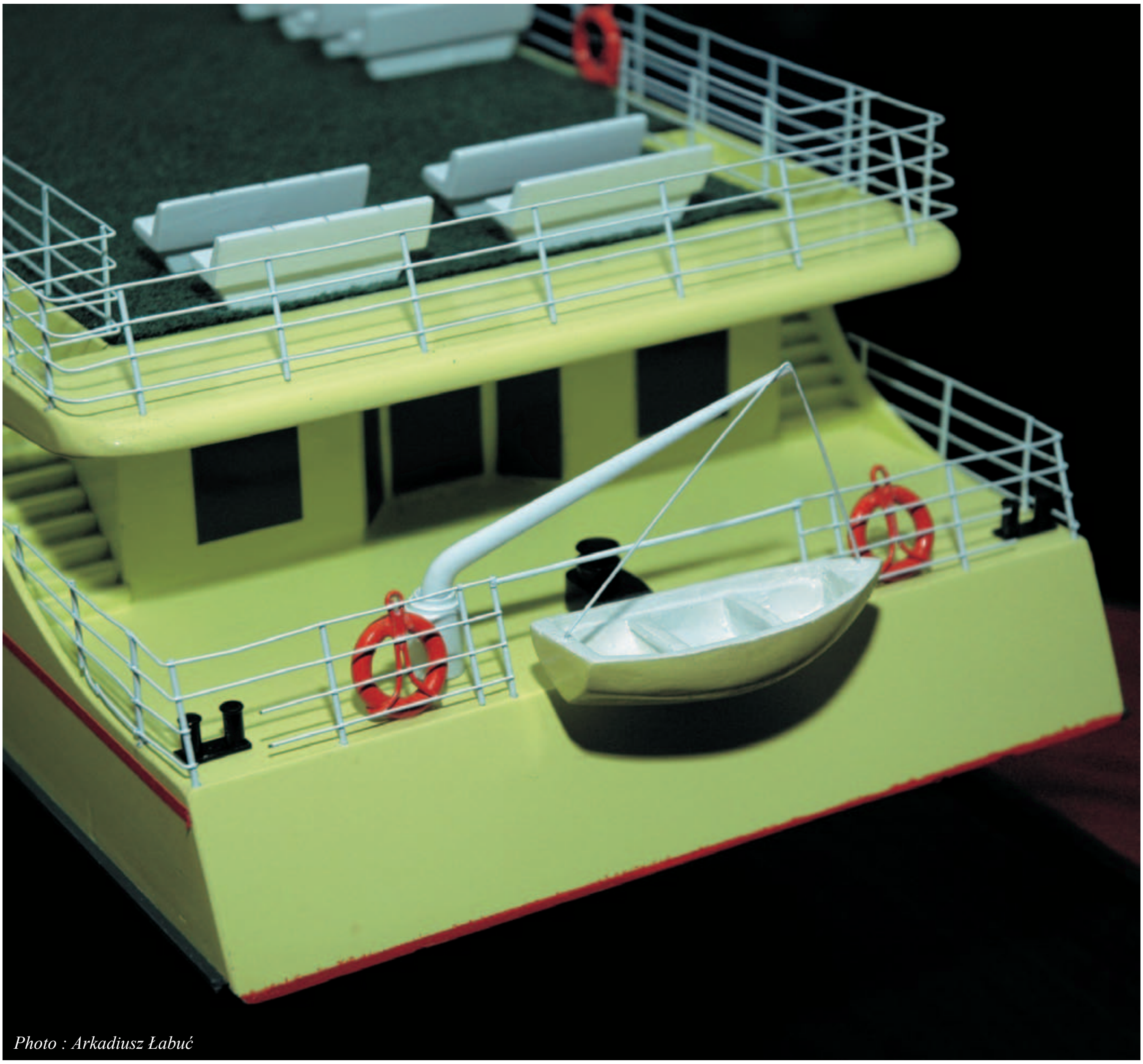

Photo : Arkadiusz Łabuć