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Seakeeping software for the analysis of a ship's seaworthiness

Żaneta Cepowska[1], Tomasz Cepowski[2]

[1] Towarzystwo Krzewienia Wiedzy o Morzu
70-500 Szczecin, ul. Wały Chrobrego 1–2, e-mail: psm@szkolamorska.pl
[2] Maritime University of Szczecin
70-500 Szczecin, ul. Wały Chrobrego 1–2, e-mail: t.cepowski@am.szczecin.pl

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Abstract

The article presents the *Seakeeping* research software, developed for the computation of a ship's motions in regular and irregular waves on the basis of the following ship parameters: length between perpendiculars, beam, draught, block coefficient and transverse initial metacentric height. The software implements approximating functions of amplitude-phase characteristics of rolling, heaving, and pitching, developed by the author by means of artificial neural networks. The software determines transfer functions for the phenomena accompanying the rolling motion, such as slamming, green water, propeller surfacing, vertical acceleration forward and on the bridge. The article discusses possible uses of the software in scientific research, ship design and operation, and for educational purposes.

Introduction

Effective methods of projecting a ship's motions in waves are key tools in the theory of shipbuilding. However, existing methods are data intensive, and data is usually sparse in the initial stages of design. This research has the goal of reducing this data shortage problem by developing simplified yet accurate mathematical equations capable of estimating a ship's seaworthiness on the basis of its basic design parameters. The results of the research (Szelangiewicz & Cepowski, 2001a; 2002) include analytical equations that enable the approximation of the amplitude-phase characteristics of the following behaviours:

- **rolling:**

$$Y_\Phi(\omega) = \frac{a_\Phi \cdot \sin\beta_w}{\sqrt{\left(1 - \frac{\omega^2}{\omega_{\Phi 0}^2}\right)^2 + \left(b_\Phi \frac{\omega}{\omega\omega_{\Phi 0}}\right)^2}} \tag{1}$$

$$\varepsilon_\Phi(\omega) = \varepsilon_0 + \mathrm{arctg}\left(\frac{b_\Phi \cdot \omega_{\Phi 0} \cdot \omega}{\omega_{\Phi 0}^2 - \omega^2}\right) \tag{2}$$

where:
$Y_\Phi(\omega)$ – amplitude characteristic of rolling [–], transfer function of roll motion;
$\varepsilon_\Phi(\omega)$ – phase characteristic of rolling [°];
ω – wave frequency [s^{-1}];
β_w – wave direction angle relative to ship [°];
$\omega_{\Phi 0}$ – natural wave frequency [s^{-1}];
a_Φ, b_Φ, ε_0 – values approximated by means of artificial neural networks:

$$a_\Phi = \left(\left[A_{BK}, B, d, \nabla, GM, \frac{L_{pp}}{B}, C_B\right] \times \right.$$
$$\left. \times A_{1a\Phi} + B_{1a\Phi}\right) \times A_{2a\Phi} + B_{2a\Phi} \tag{3}$$

$$b_\Phi = (((\left[A_{BK}, B, d, \nabla, GM\right] \times A_{1b\Phi} + B_{1b\Phi}) \times$$
$$\times A_{2b\Phi} + B_{2b\Phi}) \times A_{3b\Phi} + B_{3b\Phi}) \times$$
$$\times A_{4b\Phi} + B_{4b\Phi} + 0{,}0005 \cdot V \tag{4}$$

$$\varepsilon_0 = \left(\left[A_{BK}, B, d, \nabla, GM, \frac{L_{pp}}{B}, C_B\right] \times A_{1\varepsilon\Phi} + B_{1\varepsilon\Phi}\right) \times$$
$$\times A_{2\varepsilon\Phi} + B_{2\varepsilon\Phi} \tag{5}$$

where:
A_{BK} – bilge keel surface area [m^2];
L_{pp} – length between perpendiculars;
B – beam [m];
d – draught [m];
∇ – volume of displacement [m^3];
GM – transverse initial metacentric height [m];
C_B – block coefficient;
$W_{i\Phi}$ – column vectors of input variables (design parameters), where: $i = a_\Phi, b_\Phi, \varepsilon_0$;
$A_{1t\Phi}, A_{2t\Phi}, A_{3t\Phi}, A_{4t\Phi}$ – matrices of weight coefficients, where: $t = a_\Phi, b_\Phi, \varepsilon_0$;
$B_{1t\Phi}, B_{2t\Phi}, B_{3t\Phi}, B_{4t\Phi}$ – vectors of constants, where: $t = a_\Phi, b_\Phi, \varepsilon_0$;
V – ship's speed [m/s];

- **pitching:**

$$Y_\Theta(\omega) = \frac{c_\Theta}{\left(\left(1-\frac{\omega^2}{a_\Theta^2}\right)^2 + \left((b_\Theta - 0.011\cdot V)\frac{\omega}{a_\Theta}\right)^2\right)^3} \qquad (6)$$

$$\varepsilon_\Theta(\omega) = \left(\left(W_{\varepsilon\Theta} \times A_{\varepsilon 0\Theta}\right) \times A_{\varepsilon 1\Theta} + B_{\varepsilon 1\Theta}\right) \times A_{\varepsilon 2\Theta} + B_{\varepsilon 2\Theta} \qquad (7)$$

where:
$Y_\Theta(\omega)$ – amplitude characteristic of pitching [–];
$\varepsilon_\Theta(\omega)$ – phase characteristic of pitching [º];
$a_\Theta, b_\Theta, c_\Theta$ – parameters dependent on design parameters, derived from the formula below:

$$\begin{bmatrix} a_\Theta \\ b_\Theta \\ c_\Theta \end{bmatrix} = \left(\left(\left(\left[L_{pp}/B, d, C_B, \nabla, \beta_w, \beta_w^2, \beta_w^3\right] \times A_{1\Theta} + B_{1\Theta}\right) \times A_{2\Theta} + B_{2\Theta}\right) \times A_{3\Theta} + B_{3\Theta}\right) \times A_{4\Theta} + B_{4\Theta} \qquad (8)$$

where:
$A_{1\Theta}, A_{2\Theta}, A_{3\Theta}, A_{4\Theta}$ – matrices of weight coefficients;
$B_{1\Theta}, B_{2\Theta}, B_{3\Theta}, B_{4\Theta}$ – column vectors of constants;

- **heaving:**

$$Y_Z(\omega) = \left(\left(\left[L_{pp}, \frac{L_{pp}}{B}, B, \frac{B}{d}, d, C_B, \nabla, V\right] \times A_{0Z}\right) \times A_{1Z} + B_{1Z}\right) \times A_{2Z} + B_{2Z} \qquad (9)$$

$$Y_Z(\omega) = \left(\left(\left[L_{pp}, \frac{L_{pp}}{B}, B, \frac{B}{d}, d, C_B, \nabla, V\right] \times A_{0Z}\right) \times A_{1Z} + B_{1Z}\right) \times A_{2Z} + B_{2Z} \qquad (10)$$

where:
$Y_z(\omega)$ – amplitude characteristic of heaving [–];
$\varepsilon_z(\omega)$ – phase characteristic of heaving [º];
$A_{0Z}, A_{\varepsilon 0Z}$ – unit matrices of normalizing coefficients;
$A_{1Z}, A_{2Z}, A_{\varepsilon 1Z}, A_{\varepsilon 2Z}$ – matrices of weight coefficients;
$B_{1Z}, B_{2Z}, B_{\varepsilon 1Z}, B_{\varepsilon 2Z}$ – column vectors of constants (or bias).

The research conducted by the authors (Szelangiewicz & Cepowski, 2001a; 2002) shows that the equations presented above are characterized by a high accuracy of approximation.

Equations (1)–(10) enable modelling of seaworthiness based on basic ship design parameters. However, the underlying mathematical model is highly complex.

The objective of the research discussed here is to describe computer software that uses equations (1)–(10) to estimate a ship's seaworthiness from its basic design parameters. An additional goal of the research was to develop software capable of analyzing a ship's motion in waves.

The research led to the development of the *Seakeeping* software which uses object-oriented Delphi programming language.

Seakeeping software

The key component of *Seakeeping* is the module that uses equations (1)–(10) to estimate the amplitude-phase characteristics of rolling, pitching and heaving as a function of basic ship design parameters. The module provides computations of transfer functions and static parameters of a ship's roll motion and such accompanying phenomena as:

- slamming;
- green water;
- propeller surfacing; and
- the vertical acceleration of any component of the ship.

Figure 1 presents the underlying algorithm of the *Seakeeping* seaworthiness projection module. Computations of rolling in irregular waves have been derived from the equations developed by Bhattacharyya (1978) and Dudziak (2008). Spectral density functions of irregular wave energy have been generated for:

- the ITCC spectrum;
- the JONSWAP spectrum for the North Sea;
- the JONSWAP spectrum for the North Sea during a storm; and
- the Bretschneider spectrum.

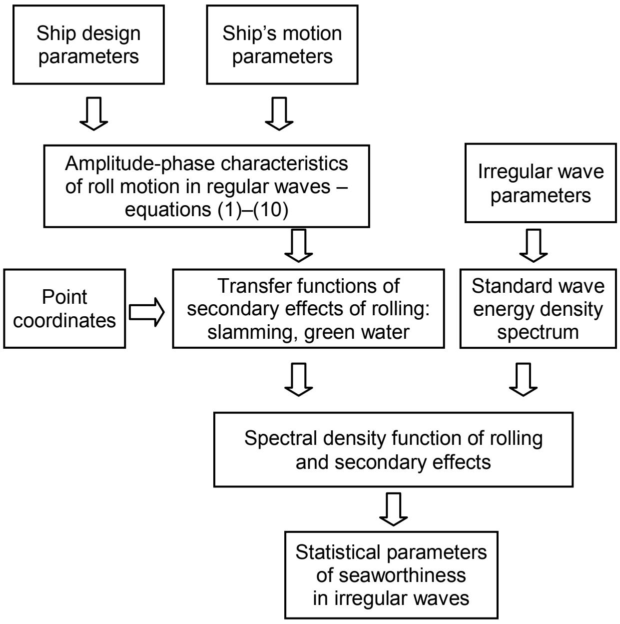


Figure 1. Seakeeping seaworthiness projection module

On the basis of the linear theory of roll motion, *Seakeeping* calculates the above types of ship motions and the accompanying phenomena in irregular waves described by the following statistical parameters:

- variance;
- significant amplitudes;
- standard deviation;
- probability of occurrence;
- number of instances per hour;
- number of instances per 100 significant waves.

Figure 2 presents the *Seakeeping* interface with the ship design parameters module, the rolling transfer function module and the wave energy density spectrum module.

In addition to the functionality of seaworthiness projection, *Seakeeping* enables:

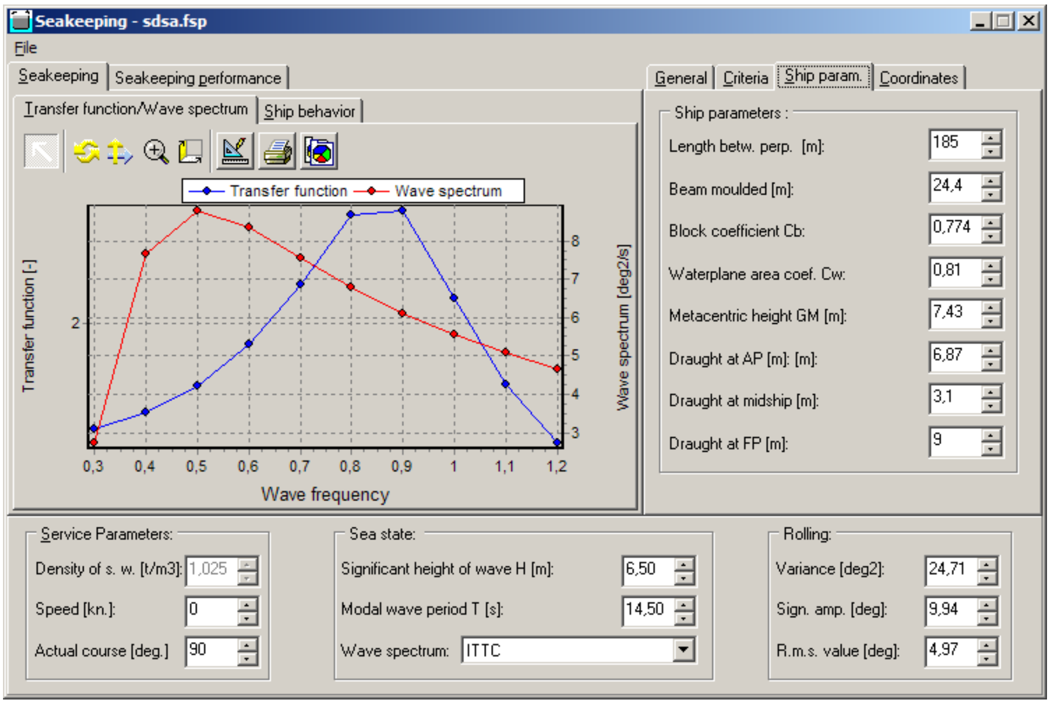
- assessment of ship's performance;
- assessment of ship's seaworthiness depending on motion parameters.

Assessment of a ship's performance by *Seakeeping* software

Seaworthiness is assessed by means of a variety of values and indices. An interesting approach to assessing seaworthiness was described by Karppinen (1978), who presented a "Seakeeping Performance Index" to assess a ship's performance on a specified navigational route.

Assuming a specified navigational route and sea state, a ship's performance is determined by waves causing roll motion and associated phenomena. Having determined threshold levels for rolling motion and accompanying phenomena, it is possible to derive the probability of not exceeding these thresholds. Such values can be determined by means of the Γ function, which takes values of 1 and 0, respectively, when roll motion and accompanying phenomena do and do not exceed threshold levels (Szelangiewicz, 2000).

Based on the values of Γ, the aggregate probability can be calculated, where $\Gamma_N = 1$ for all of the



Ship parameters :
Length betw. perp. [m]: 185
Beam moulded [m]: 24,4
Block coefficient Cb: 0,774
Waterplane area coef. Cw: 0,81
Metacentric height GM [m]: 7,43
Draught at AP [m]: [m]: 6,87
Draught at midship [m]: 3,1
Draught at FP [m]: 9

Service Parameters:
Density of s. w. [t/m3]: 1,025
Speed [kn.]: 0
Actual course [deg.] 90

Sea state:
Significant height of wave H [m]: 6,50
Modal wave period T [s]: 14,50
Wave spectrum: ITTC

Rolling:
Variance [deg2]: 24,71
Sign. amp. [deg]: 9,94
R.m.s. value [deg]: 4,97

Figure 2. *Seakeeping* interface

ship's motions. The probability is expressed as the E_T performance index derived from the following equation (Szelangiewicz, 2000):

$$E_T = \\ = \sum_A \sum_S \sum_\mu \sum_{HT} \sum_V \sum_\psi [P_T(\Gamma_1, \Gamma_2, ..., \Gamma_N = 1)] \tag{11}$$

where:

E_T – performance index;

P_T – probability with which the ship navigates in a certain area and certain sea state, derived from the following equation (Szelangiewicz, 2000):

$$P_T = f_A \cdot f_S \cdot f_\mu \cdot f_{HT} \cdot f_V \cdot f_\psi \tag{12}$$

where:

P_T – probability;

f_A – probability of the ship navigating in a defined sea area;

f_S – probability of the ship navigating during a defined season;

f_μ – probability of waves coming from a defined direction during a defined season and in a defined sea area;

f_{HT} – probability of occurrence of a defined significant wave height H_S and characteristic wave period T for a defined direction, during a defined season and in a defined sea area;

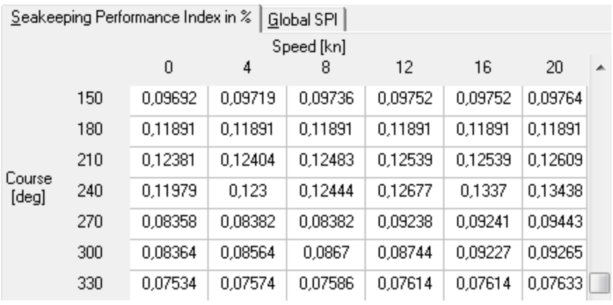
f_V – probability of the ship attaining the assumed speed V;

f_ψ – probability of the ship being on the assumed course ψ.

The E_T performance index, in general, refers to a part of the assumed ship's operation period in a defined sea area or on a defined route, during which particular criteria, in aggregate or individually, do not exceed their threshold levels. Given the assumed ship's operation period on a defined navigational route for a specified period, such as one year, the E_T index can be used to determine the number of days for which the ship will not encounter any dangers to navigation.

Seakeeping implements a module for computing the performance index described above. Deriving this index requires, among other things, a knowledge of wave frequency spectrum data for a given navigational route.

Figure 3 presents partial values of the performance index, depending on the ship's motion parameters, as calculated by the *Seakeeping* software. The total value of the index in this case is the aggregate of all the partial values.



Course [deg]	Speed [kn] 0	4	8	12	16	20
150	0,09692	0,09719	0,09736	0,09752	0,09752	0,09764
180	0,11891	0,11891	0,11891	0,11891	0,11891	0,11891
210	0,12381	0,12404	0,12483	0,12539	0,12539	0,12609
240	0,11979	0,123	0,12444	0,12677	0,1337	0,13438
270	0,08358	0,08382	0,08382	0,09238	0,09241	0,09443
300	0,08364	0,08564	0,0867	0,08744	0,09227	0,09265
330	0,07534	0,07574	0,07586	0,07614	0,07614	0,07633

Figure 3. Partial values of performance index, depending on the course angle and the ship's speed

Application of *Seakeeping* software in the development of ship design parameters

Seakeeping can be applied in developing ship design parameters needed for specific performance characteristics on a given navigational route. The E_T performance index computation module can be used for this purpose.

Table 1 presents a list of design variants and the performance index values calculated by the *Seakeeping* program for all of the parameters of seaworthiness in aggregate, and for each of them individually. Based on the table data, the design variant with the best performance index can be selected. For the data in the design task presented, the best variant in terms of seaworthiness parameters is variant No. 4.

Table 1. Ship design parameters: L – length, B – beam, Cb – block coefficient, GM_0 – transverse initial metacentric height, T – draught, performance indices: E_T – for all seaworthiness parameters, $E_{T\text{roll}}$ – for roll motion, $E_{T\text{slam}}$ – for slamming, $E_{T\text{prop}}$ – for propeller surfacing, $E_{T\text{green}}$ – for green water, values calculated in *Seakeeping*

Variant	L [m]	B [m]	Cb [–]	GM_0 [m]	T [m]	E_T	$E_{T\text{roll}}$	$E_{T\text{slam}}$	$E_{T\text{prop.}}$	$E_{T\text{green}}$
1	144.6	24.1	0.67	2	8.6	0.87	0.98	0.89	0.87	0.77
2	152.8	23.5	0.71	1.85	7.8	0.85	0.89	0.89	0.85	0.73
3	161	23	0.75	2.41	7.2	0.81	0.88	0.88	0.82	0.7
4	170.3	22.7	0.78	2.92	6.7	0.77	0.94	0.87	0.8	0.67
5	184.2	30.7	0.78	3	10.2	0.94	0.88	0.94	0.91	0.86
6	192.4	29.6	0.75	3	10.6	0.94	0.95	0.94	0.91	0.86
7	219.1	31.3	0.71	3.98	9.2	0.9	0.97	0.91	0.89	0.8
8	229.5	30.6	0.67	3.05	9.6	0.9	0.98	0.91	0.88	0.8

Application of the *Seakeeping* software for optimization of a ship's motion parameters

Weather Weather navigation centers often provide short-term forecasts of ship roll motion, which can be used to change course in order to bypass areas in which dangerous waves are likely to occur.

This kind of simulation typically requires, in addition to special software, a detailed technical specification of the ship's design. However, such data are not always available, a circumstance that makes it very difficult, if not impossible, to project a ship's seaworthiness.

The *Seakeeping* software presented here tackles this problem by enabling short-term forecasting of a ship's roll motion and secondary phenomena based on the ship's basic geometric parameters instead of a detailed list of technical specifications.

Seakeeping also facilitates assessment of seaworthiness based on seakeeping criteria whose standard values can be determined from data presented by Szelangiewicz (2000). Figure 4 presents the module of assessment of a ship's seaworthiness depending on the ship's service parameters – that is to say, on the speed and wave direction angle relative to the ship. The results are marked in red and green. The red area represents the range of dangerous parameters of ship's motion, i.e. speed V and wave direction angle relative to ship β_w, for which the projected values of selected seaworthiness parameters exceed the software preset maximum allowable values. The green area, on the other hand, represents a safe range of values for speed V and angle β_w.

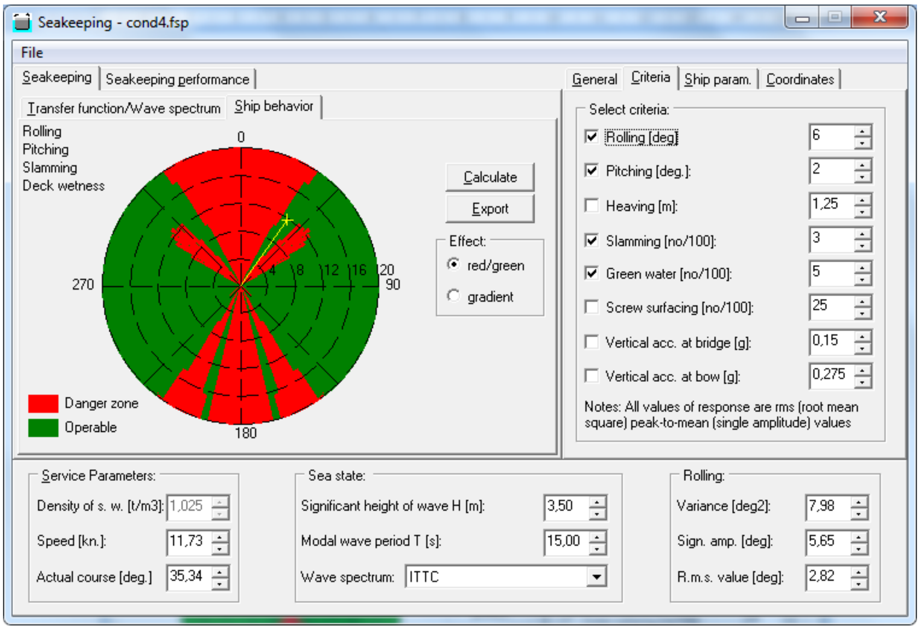
It follows from Figure 4 that, for the ship under review and under the assumed wave conditions (significant wave height $H_s = 3.5$ m and wave characteristic period 15 s), the ship's course must be altered to avoid dangerous rolling, pitching, slamming and green water. Alteration of the course to one at which the wave angle relative to the ship, β_w, is 35°, will result in the occurrence of roll motion of a significant amplitude of 5.65°.

Application of the *Seakeeping* software for educational purposes

Thanks to its functionalities, *Seakeeping* is useful tool for educational purposes. The software is used in the Postsecondary Maritime School in Szczecin, a partner school of the Association for Knowledge of the Sea (*Towarzystwo Krzewienia Wiedzy o Morzu*).

The Postsecondary Maritime School in Szczecin enables students to obtain the diploma of deck or engineer officer and gain qualifications necessary to find employment on ships all over the world within a relatively short period of time. It admits students who have completed a secondary school of general education or secondary technical school with or without the graduation diploma (*Matura*). The school prepares students for work in the deck or engineering department on seagoing ships, to take the Officer of the Watch examination. It also opens a path leading to further professional development (see www.szkola.morska.pl, 2015).

Graduates of the Postsecondary Maritime School in Szczecin are fully qualified to sit the Officer of the Watch examination held by the



Effect:
● red/green
○ gradient

Select criteria:
☑ Rolling [deg]: 6
☑ Pitching [deg.]: 2
☐ Heaving [m]: 1,25
☑ Slamming [no/100]: 3
☑ Green water [no/100]: 5
☐ Screw surfacing [no/100]: 25
☐ Vertical acc. at bridge [g]: 0,15
☐ Vertical acc. at bow [g]: 0,275

Notes: All values of response are rms (root mean square) peak-to-mean (single amplitude) values

Service Parameters:
Density of s. w. [t/m3]: 1,025
Speed [kn.]: 11,73
Actual course [deg.]: 35,34

Sea state:
Significant height of wave H [m]: 3,50
Modal wave period T [s]: 15,00
Wave spectrum: ITTC

Rolling:
Variance [deg2]: 7,98
Sign. amp. [deg]: 5,65
R.m.s. value [deg]: 2,82

Figure 4. Seaworthiness projection and assessment module

Examination Commission at the Maritime Office, and obtain the diploma of deck or engineer officer, required for employment on ships operated by Polish and foreign ship-owners. There are two specializations available at the School: marine navigation technician, and marine engineer technician (see www.szkolamorska.pl, 2015).

With a view to meeting formal requirements (Rozporządzenie, 2005), students of both specializations are required to gain knowledge of shipbuilding theory within the scope of use of computer software for short-term forecasting of roll motion. For this purpose, the following simulation exercises in shipbuilding theory are conducted in the *Seakeeping* software:

- assessment of ship's seaworthiness under assumed wave conditions;
- optimization of ship's motion parameters with a view to seaworthiness;
- the impact of ship's size and proportions of her basic dimensions on roll motion;
- the impact of transverse initial metacentric height on the roll motion amplitude;
- selection of motion parameters to avoid the resonance effect.

Conclusions

The innovative research software presented in the article is based on the authors' original method (Szelangiewicz & Cepowski, 2001; 2001a). Its comprehensive application includes:

- design and research analyses;
- weather navigation – for the purpose of optimization of ship's motion parameters;
- educational purposes – for the purpose of teaching the theory of shipbuilding.

Seakeeping can be specifically used:

- to determine amplitude-phase characteristics of rolling, pitching and heaving;
- to derive transfer functions for the phenomena accompanying the roll motion, such as slamming, green water, propeller surfacing, vertical acceleration forward and on the bridge;
- for short-term forecasting of the above ship's motions and the accompanying phenomena;
- visual assessment of seaworthiness by means of a pie chart;
- computation of the performance index in accordance with (Karppinen, 1987; Szelangiewicz, 2000).

The *Seakeeping* software can produce the outputs described above with the following ship design input parameters:

- length between perpendiculars;
- beam;
- draught;
- block coefficient;
- transverse initial metacentric height;
- the parameters of irregular waves and standard wave energy density spectra.

This innovative software facilitates analysis of motions of a ship (or a group of ships) in waves by means of the performance index, thus enabling comprehensive analyses for the purposes of:

- development of ship design;
- selection of an appropriate ship for a particular navigational route;
- assessment of a ship's motion on a particular navigational route by means of a clear-cut index.

In these terms, the software is trailblazing, since the existing software available in the market does not feature all of these functionalities. The software is an innovative tool for the analysis of a ship's hydro-mechanical properties, and for the development of shipbuilding theory.

The software can also be used in maritime schools for educational purposes within the scope of the theory of shipbuilding.

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