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Application of Artificial Neural Networks to investigations of ship seakeeping ability

SUMMARY

In order to optimize the ship design at its conceptual and preliminary stages with taking into account also seakeeping criteria, simple and simultaneously exact relationships between the basic ship design parameters and seakeeping ability are necessary. The wave-induced motions of the ship in irregular waves as well as phenomena accompanying the motions, are determined on the basis of the frequency transfer functions of the ship motions in regular waves.

In this paper an approximation method is presented for determination of such transfer functions with the use of the Artificial Neural Networks (ANNs). The attached results of numerical calculations show that the method provides exact data for ships of very different sizes, within wide ranges of ship velocity and direction of wave relative to the ship.

Part I

MODELLING THE WAVE-INDUCED SHIP MOTIONS BY MEANS OF THE ARTIFICIAL NEURAL NETWORKS

INTRODUCTION

In ship design theory, new unconventional methods are more and more used, to which a. o. multi-criterial optimization of ship parameters is also included [11], [12]. Among optimization criteria there are also those connected with ship seakeeping ability.

To make the multi-criterial assessment of the design solutions effective, its particular conditions and criteria should be described by means of possibly simple functions containing main design parameters of the ship. In the published optimization methods the ship seakeeping criteria are taken into account to a small extent, or neglected at all. The reason is the wave-induced motions of ships and the accompanying phenomena are very hard to describe by simple and simultaneously exact functions of only few, basic ship design parameters. It is relatively easy to assess seakeeping ability of the existing or designed ships for which relevant documentation (e.g. underwater hull form, centre-of-mass coordinates at assumed service states) is avaliable. In this paper a prediction method of ship seakeeping ability is presented, applicable at the preliminary ship design stage when only its basic design parameters, but not yet an exact ship hull form, are known. This way in ship design optimization process it would be possible to a greater extent to take into account ship seakeeping criteria.

SEAKEEPING ABILITY IN SHIP DESIGN PROCESS

During ship sailing in waves the direct effects of wave-ship interaction are ship motions and their derivatives : velocities and accelerations. The secondary effects accompanying the wave-induced ship motions are : deck wetness, propeller emerging, slamming , worsened stability, additional dynamic hull loads.

Initially, in ship design process attention has paid only to ship's rolling period. However, after many ship disasters in rough weather a greater group of hazardous phenomena among ship seakeeping ability has been taken into account [5]. These phenomena are the following :

- rolling
- pitching
- accelerations
- slamming
- propeller emerging
- deck wetness.

This group is not definitely closed , and it only reflects the phenomena specified by many authors. Relevant acceptance criteria were proposed in [5] and [10]. If they are not exceeded for the ship sailing at the speed V and course angle ψ at given weather conditions (characterized by the wave parameters : the wave height H, period T and geographical direction angle μ), the ship is assumed fulfilling her mission safely.

The above specified phenomena can be presented in the form of frequency transfer functions of particular wave-induced ship motions, which should be approximated by means of possibly simple, and simultaneously exact functions dependent only on ship design parameters.

The approximating functions are usually elaborated on the basis of statistical analyses of the seakeeping ability of similar ships. A relevant data base can be elaborated by using measurement records obtained from existing ships , ship model tests, or calculation results computed for a group of ship hull forms by means of exact computer programs e.g. [1], [2], [6]. Such approach not always provides appropriate results as the elaborated formulas deal only with e.g. a given hull form, wave direction respective to ship, or a given ship motion component.

In this paper a simpler, and simultaneously more general method is proposed which makes use of the algorithms based on artificial intelligence in the form of ANN, and makes it possible to simulate non-linear phenomena.

ARTIFICIAL NEURAL NETWORKS

A numerical, neural network model is based on the biological neural system (Fig.1.) and its way of signal transfer. In the result of a learning process the neural network transforms the input signal $X[x_1, x_2, ..., x_n]$ into the output vector $Y[y_1, y_2, ..., y_m]$ in a linear or non-linear way :

$$f : X \rightarrow Y \tag{1}$$

The neural network consists of several layers. Each layer consists of many nodes. In Fig.1. three layers are shown : the *input layer*, *output layer* and, between them, the *hidden layer*.

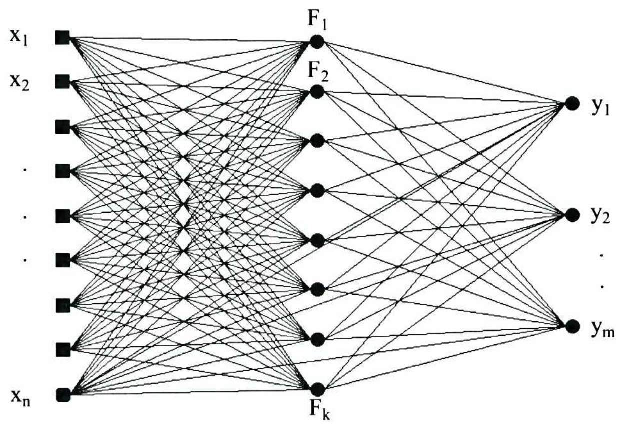

Fig.1. *General structure of the Artificial Neural Network [8]*
$x_1, x_2, ...,x_n$ – input signals, $y_1, y_2, ..., y_m$ – output signals,
$F_1, F_2, ..., F_k$ – hidden layer nodes

Values from the preceding layers are transferred through the neurons. Signals coming to a given neuron (i.e. the input signals x_j) are multiplied by the weighting factors w_{ij} and summed up by the adder Σ which calculates the output value u_i of i-th neuron (Fig.2)

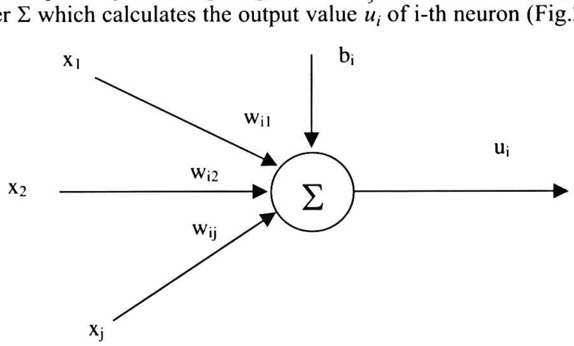

Fig. 2. *Signals coming to and departing from a single neuron*

Additionally, the constant component b_i, called *bias*, is introduced. The output value u_i is then expressed as follows :

$$u_i = \sum_{j=1}^{N} w_{ij} \cdot x_j + b_i \tag{2}$$

where :

w_{ij} – weighting factors
x_j – input signal
u_i – output signal
b_i – bias
N – number of nodes.

The ANN learning process is carried out on the basis of data available from experiments or theoretical calculations.

The process is performed in the following way : the data vector X_{Nx1} is introduced as the input and the result vector Y_{Mx1} as the output, and the network itself makes the following transformation :

$$X_{Nx1} \rightarrow Y_{Mx1} \tag{3}$$

The learning process is aimed at determining such values of the weighting factors w_{ij} and bias b_i for which the network response complies with the results vector.

After completing the learning process the network is tested by putting-in known data and comparing the calculated results with the model results.

For solving technical problems the error-backpropagating neural network, from among many types of ANN, is usually applied.

The structure of such network consists of three kinds of layers : input layer, hidden layers and output layer. The neurons of each layer are not connected to each other, however they are linked up to the neurons of other layers. Although combinations of neuron connections can be different, the following scheme is most often used : all neurons of each layer are connected to all neurons of neighbouring layers (Fig.1). The error-backpropagation algorithm consists in a reverse procedure of improvement of the weighting factors (network learning), i.e. that directed from the input layer back to the first hidden layer.

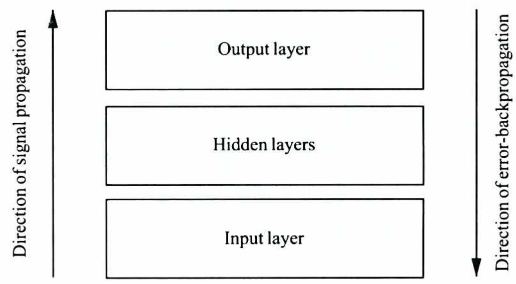

Fig.3. *The error-backpropagating neural network*

APPLICATION OF THE ANNs TO DETERMINING THE FREQUENCY TRANSFER FUNCTIONS OF SHIP WAVE-INDUCED MOTIONS

As far as predicting the ship seakeeping ability is concerned the most interesting property of the ANN is its ability to interpolate and predict. The set of the ship design parameters $(x_1, x_2, ..., x_n)$ can be input data to the ANN, and the ship motions transfer functions Y_{Gm} calculated by means of an exact numerical software or measured experimentally, can serve as a model, i.e. learning set. The so trained ANN can be used as a simulator for generating the ship motions frequency transfer functions on the basis of the assumed ship design parameters.

The approximation of the model, ship motions frequency transfer functions consists in searching for functional relationships of the following form :

$$Y_m = f_m (x_1, x_2, ..., x_n) \tag{4}$$

where :

Y_m – amplitude transfer function of m-th wave-induced ship motion, obtained from approximation
f_m – analytical function for m-th wave-induced ship motion
$x_1, x_2, ..., x_n$ – ship design parameters.

The ship design parameters $x_1, x_2, ..., x_n$ should be so selected as to make it possible to cover a large ship-size group, and also relevant ranges of other design criteria (e.g. deadweight, manoeuvrebility, propulsion power, building and operation costs).

On the basis of [1], [3], [5], and [7] it was determined which ship design parameters decisively influence ship wave-induced motions (Tab.1).

Tab.1. *Ship design parameters most influencing ship wave-induced motions*

Wave-induced motions	Ship design parameters
Rolling	L/B , B/d , C_B , ∇ , A_{BK} , GM , H/d
Pitching	L/B , B/d , C_B , ∇ , C_F
Heaving	L/B , B/d , C_B , ∇ , C_F

where :

- A_{BK} – bilge keel area
- B – ship breadth
- C_B – block coefficient
- C_F – water-plane area coefficient
- d – ship draught
- GM – transverse metacentric height
- H – ship depth
- L – ship length between perpendiculars
- ∇ – immersed volume.

The ship motion frequency transfer functions are also influenced, apart from the above mentioned design parameters, by the ship speed V and wave direction angle β_w respective to ship course.

Assumptions for the presented investigations

In order to find approximate amplitude characteristics of ship wave-induced motions by means of ANNs the following ranges or values of the basic design parameters were assumed :

Tab.2. *Assumed ranges or values for basic design parameters*

Basic design parameter	Range or value
∇	20 000 ÷ 95 000 m^3
L/B	6 ÷ 7.5
B/d	2.8 ÷ 3.4
C_B	0.67 ÷ 0.78
hull form	series 60
regular wave amplitude ζ_A	1 m
wave direction angle β_w	0° ÷ 180° with 22.5°step
regular wave frequency ω	0.3 ÷ 1.2 s^{-1}
ship speed V	0 ÷ 10 m/s with 2 m/s step

On this basis, and by making use of the orthogonal table given in [3], 16 calculation variants of frequency transfer functions of ship wave-induced motions were selected to form knowledge base for learning the ANN (Tab.3).

Tab.3. *Assumed design variants for frequency transfer functions calculation of ship wave-induced motions*

No.	Code number	∇	Code number	L/B	Code number	B/d	Code number	C_B
1	1	20 000	1	6	1	2.8	1	0.67
2	1	20 000	2	6.5	2	3	2	0.71
3	1	20 000	3	7	3	3.2	3	0.75
4	1	20 000	4	7.5	4	3.4	4	0.78
5	2	45 000	1	6	2	3	4	0.78
6	2	45 000	2	6.5	1	2.8	3	0.75
7	2	45 000	3	7	4	3.4	2	0.71
8	2	45 000	4	7.5	3	3.2	1	0.67
9	3	70 000	1	6	3	3.2	2	0.71
10	3	70 000	2	6.5	4	3.4	1	0.67
11	3	70 000	3	7	2	3	4	0.78
12	3	70 000	4	7.5	1	2.8	3	0.75
13	4	95 000	1	6	4	3.4	3	0.75
14	4	95 000	2	6.5	3	3.2	4	0.78
15	4	95 000	3	7	2	3	1	0.67
16	4	95 000	4	7.5	1	2.8	2	0.71

On the basis of Tab.3. for each of the investigated ships :

- ⇨ values of the design parameters were determined
- ⇨ location of the transverse metacentric point GM was calculated with the help of hydrostatic curves, and
- ⇨ metacentric height KM was assumed, shown in (Tab.4).

Tab.4. *Values of the design parameters, location of transverse metacentric point and assumed metacentric heights for the investigated ships*

No.	L [m]	B [m]	d [m]	C_B	KM [m]	GM [m]
1	144.60	24.10	8.60	0.67	9.79	2.00
2	152.80	23.50	7.80	0.71	9.65	1.85
3	161.00	23.00	7.20	0.75	9.61	2.41
4	170.30	22.70	6.70	0.78	9.62	2.92
5	184.20	30.70	10.20	0.78	12.68	3.00
6	192.40	29.60	10.60	0.75	12.11	3.00
7	219.10	31.30	9.20	0.71	13.18	3.98
8	229.50	30.60	9.60	0.67	12.65	3.05
9	225.00	37.50	11.70	0.71	15.58	3.88
10	246.40	37.90	11.10	0.67	15.91	4.81
11	236.60	33.80	11.30	0.78	13.95	3.50
12	245.30	32.70	11.70	0.75	13.39	3.00
13	249.60	41.60	12.20	0.75	17.66	5.46
14	254.20	39.10	12.20	0.78	16.35	4.15
15	275.10	39.30	13.10	0.67	16.07	4.50
16	276.00	36.80	13.10	0.71	14.99	4.50

The applied ANNs were designed and tested by means of the computer software Tlearn V. 1.0.3 applicable to designing the error - - backpropagating neural networks. To form the learning set for the networks the model frequency transfer functions were calculated by means of GRIM software based on the 2-D flow theory making use of multipolar potentials.

Rolling

On the basis of the so-obtained characteristics the following model of the rolling transfer function was assumed :

$$Y_\Phi(\omega) = \frac{a \cdot \sin\beta_w}{\sqrt{\left(1 - \frac{\omega^2}{\omega_{\Phi 0}^2}\right)^2 + \left(b \frac{\omega}{\omega_{\Phi 0}}\right)^2}} \qquad (5)$$

where :

- a – a coefficient equivalent to the Froude-Krylov reduction coefficient
- b – a coefficient equivalent to the dimensionless dumping coefficient
- β_w – wave direction angle relative to ship
- ω – regular wave frequency
- $\omega_{\Phi 0}$ – natural rolling frequency.

The natural rolling frequency $\omega_{\Phi 0}$ was calculated in a simplified way by means of the following formula :

$$\omega_{\Phi 0} = \sqrt{\frac{g \cdot m \cdot GM}{I_{xx} \cdot (1 + k_{xx})}} \qquad (6)$$

where :

- g – acceleration gravity
- m – ship mass
- GM – transverse metacentric height
- I_{xx} – transverse inertia moment of ship mass
- k_{xx} – added mass coefficient.

Three seperate ANNs were used to determine analytical relationships between the coefficients a, b and k_{xx} and the ship design parameters (Tab.5).

Tab.5. Parameters of the ANNs for rolling

Coefficient	ANN structure	Input parameters	Mean square error* [–]
a	7 x 16 x 1	W_a=[A_{BK} ,B, d,∇, GM, L/B, C_B]	0.035
b	5 x 10 x 10 x 10 x 1	W_b = [A_{BK} ,B, d, ∇, GM]	0.005
k_{xx}	3 x 6 x 6 x 6 x 1	W_k = [B,∇, B/d]	0.003

** Relative error between the model characteristics and those calculated by the relevant ANN*

This way the coefficients a, b and k_{xx} were expressed in the matrix form by means of the following formulas :

$$a = (W_a \cdot A_{1a} + B_{1a}) \cdot A_{2a} + B_{2a} \tag{7}$$

$$b = \{[(W_b \cdot A_{1b} + B_{1b}) \cdot A_{2b} + B_{2b}] \cdot A_{3b} + B_{3b}\} \cdot A_{4b} + B_{4b} + 0.001 \cdot V \tag{8}$$

$$k_{xx} = \{[(W_k \cdot A_{1k} + B_{1k}) \cdot A_{2k} + B_{2k}] \cdot A_{3k} + B_{3k}\} \cdot A_{4k} + B_{4k} \tag{9}$$

where :

W_i – column vectors of input variables (design parameters)
A_{1i}, A_{2i}, A_{3i}, A_{4i} – matrices of weighting factors
B_{1i}, B_{2i}, B_{3i}, B_{4i} – matrices of constants
i = a, b, k
V – ship speed [knots].

To speed up the learning process of the ANNs the design parameters contained in the matrices W_i were normalized within the interval ⟨-1,1⟩ by means of the equation (10) :

$$x_{\langle -1,1\rangle} = -1 + \frac{2(x - x_{min})}{x_{max} - x_{min}} \tag{10}$$

where :

$x_{\langle -1,1\rangle}$ – value after normalization
x – value before normalization
x_{min} – minimum value of design parameter
x_{max} – maximum value of design parameter.

Pitching

For parametrization of the pitching transfer function the following model was used :

$$Y_\Theta(\omega) = \frac{t}{\left(\left(1 - \frac{\omega^2}{r^2}\right)^2 + \left(s\frac{\omega}{r}\right)^2\right)^3} \tag{11}$$

where : r, s, t – ANN coefficients dependent on design parameters.

To their determination only one ANN was used, of the parameters presented in Tab.6.

Tab.6. Parameters of the ANN for pitching

Coefficient	ANN structure	Input parameters	Mean square error [–]
r s t	8 x 16 x 20 x 12 x 3	W = [L/B, d, C_B,∇, β_w, β_w^2, β_w^3, C_F]	0.005 0.009 0.009

All the input data were normalized within the interval ⟨-1,1⟩ by means of (10).

The above given ANN can be expressed in the matrix form as follows :

$$\begin{bmatrix} r \\ s \\ t \end{bmatrix} = \{[(W \cdot A_1 + B_1) \cdot A_2 + B_2] \cdot A_3 + B_3\} \cdot A_4 + B_4 \tag{12}$$

where :

W – column vector of input variables (design parameters and wave direction angle β_w)
A_1, A_2, A_3, A_4 – matrices of weighting factors
B_1, B_2, B_3, B_4 – matrices of constants.

In the coefficient s calculated from (12) the ship speed V is not accounted for. Therefore the corrected coefficient, s_0 [14] was introduced :

$$s_0 = s - 0{,}0055 \cdot V \tag{13}$$

where : V – ship speed [knots].

Heaving

The heaving transfer function was determined directly with the use of ANN, namely the ANN generated values of that function at a discrete distribution of the frequency ω, of 0.3÷1.2 range, at 0.1 step, i.e. each of 10 network outputs, associated with a given wave frequency, generated discrete values of the heaving transfer function.

In order to obtain the possibly simplest network structure the entire model was split into nine elementary neural networks. Each of the networks generated values of the heaving transfer function for a selected value of the wave relative direction angle β_w. As it turned out, the results obtained from that model were very close to the model values. A drawback of the solution is the discrete form of the transfer function in question, however it should not impair the optimizing model because of the assumed method for assessment of ship seakeeping ability.

The ANN which determines discrete values of the heaving transfer function, was expressed in the matrix form as follows :

$$Y_z\ (\omega = \text{const}) = [(W \cdot A_0) \cdot A_1 + B_1] \cdot A_2 + B_2 \tag{14}$$

where :

W – vector of input variables (design parameters and ship speed)
A_0 – unit matrix of normalizing factors
A_1, A_2 – matrices of weighting factors
B_1, B_2 – column matrices of constants (bias).

To determine the discrete values Y_z of the heaving frequency transfer functions nine elementary ANNs of the parameters given in Tab.7. were used.

Tab.7. Parameters of the ANNs for heaving

Calculated value	Wave direction angle β_w [deg]	ANN structure	Input parameters	Mean square error [–]
Y_z at ω = const	0 22.5 45 67.5 90 112.5 135 157.5 180	8 x 11 x 11	W = [L , L/B , B , B/d , d , C_B,∇ , V]	0.020 0.020 0.021 0.016 0.017 0.016 0.020 0.022 0.021

To be continued

Appraised by Jan Kulczyk, Assoc.Prof.,D.Sc.

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Conference

SEMINAR OF SPE REGIONAL GROUP E

On 7 June this year the next seminar of the Regional Group of the Utility Foundations Section (SPE), Polish Academy of Sciences was held in Elbląg, hosted by the State High School of Technology, Elbląg.Prof.Eng.Zbigniew Walczyk, Rector of the School, after welcoming the participants, presented its organizational structure and program of education. Next, two representatives of the ALSTOM POWER firm presented the gas turbines for energy industry and NG compressors produced by the firm.

During scientific part of the Seminar three papers were read and discussed :

- *Investigation of the influence of sealing on the rotor machine dynamics* (K.Kossowski of Technical University of Gdańsk, and Z.Walczyk of State High School of Technology of Elbląg)
- *Optimization of compression of a gas turbine operating within a gas-steam system* (K. Kossowski of Technical University of Gdańsk)
- *Influence of foundations on the dynamic behaviour of power-station turbosets* (Z.Walczyk of State High School of Technology of Elbląg and H.Olszewski of Technical University of Gdańsk).

Państwowa Wyższa Szkoła Zawodowa w Elblągu

FOREIGN conference

CMEM 2001

From 4 to 6 June 2001 10th International Conference on :

Computational Methods and Experimental Measurements

was held in Alicante (Spain). From among 98 papers presented by scientists from 18 countries 9 papers were prepared by Polish authors, namely :

Within the topical group – **Damage Mechanics**

- *Modelling and computations of contact joints using ADINA FEM system* (K. Konowalski, L. Sobczak, K. Grudziński fromTechnical University of Szczecin)
- *Numerical assessment of the fatigue crack propagation in ship structural details* (J. Kozak from Technical University of Gdańsk)

Within the topical group – **Fluid Dynamics**

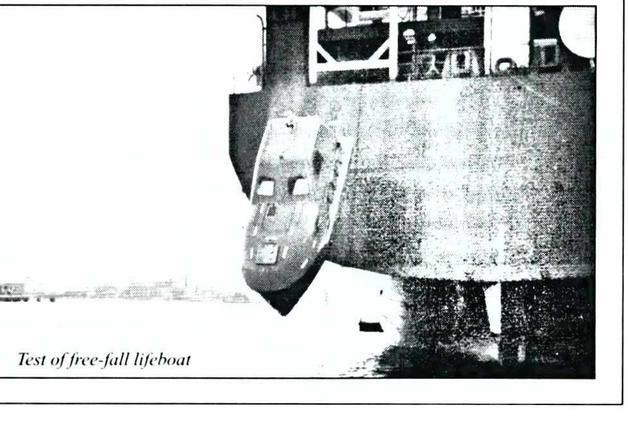
- *Experimental model for casting problems* (T.A. Kowalewski and A. Cybulski from Polish Academy of Sciences – Warszawa, T. Sobiecki from Warszawa University of Technology)
- *Experimental investigations on thermal, thermocapillary and forced convection in Czochralski crystal growth configuration* (T.A. Kowalewski (co-author) from Polish Academy of Sciences – Warszawa)

Within the topical group – **Dynamics and Vibrations**

- *Experimental verification of the mathematical model of free-fall lifeboat launching kinematics* (Z. Wiśniewski from Gdynia Maritime Academy)
- *The use of sensitivity analysis for selection of decision variables in machine tool dynamic models identification* (P. Gutowski, S. Berczyński from Technical University of Szczecin)
- *An improved method of approximating frequency characteristics in the problem of modal analysis and its applications* (S. Berczyński, M. Lachowicz, M. Pajor from Technical University of Szczecin)
- *Diagnostics of machine tool load-carrying systems weak points with static respect to stiffness criterion* (G. Szwengier, J. Skrodzewicz, D. Jastrzębski from Technical University of Szczecin)

Within the topical group – **Data acquisition and processing**

- *Filtering of experimental data at arbitarily located points of planes and surfaces* (M. Stanuszek and M. Kaja (co-authors) from Technical University of Kraków)



Test of free-fall lifeboat