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ANALYSIS OF IMPACT OF SHIP MODEL PARAMETERS ON CHANGES OF CONTROL QUALITY INDEX IN SHIP DYNAMIC POSITIONING SYSTEM

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ABSTRACT

In this work there is presented an analysis of impact of ship model parameters on changes of control quality index in a ship dynamic positioning system designed with the use of a backstepping adaptive controller. Assessment of the impact of ship model parameters was performed on the basis of Pareto-Lorentz curves and ABC method in order to determine sets of the parameters which have either crucial, moderate or low impact on objective function. Simulation investigations were carried out with taking into account integral control quality indices.

Keywords: backstepping, ship dynamic positioning, system's susceptibility

INTRODUCTION

The main ship control classification system covers a control at greater speeds and that at low speeds. It is usually assumed that ship motion at a speed higher than 2m/s [11, 14, 15, 17, 22], is that carried out at greater speeds and deals with course keeping and motion along a given trajectory. Such motion control operations are performed in two degrees of freedom (2DOF). They cover ship longitudinal motion and rotation, i.e. heading change. And, ship motion control at a speed below 2m/s concerns a precision control and covers dynamic positioning (DP) whose aim is to keep a ship in a constant position and heading at a high level of external disturbances resulting from sea environmental effects of wind, waves, sea current and shallow water acting on ship hull [19].

The manoeuvring of ship at dynamic positioning covers 3DOF control (i.e. in three directions of motion). In this case there is possible to independently control ship position (x, y) and its rotation r by changing bow heading angle relative to north.

Ship's structure and sea environment disturbances acting on it make that ship is not capable of changing direction of its motion (its orientation) on the spot. Taking into account an aim of control one strives to minimize deviations from a given position and heading by making use of ship propulsion and motion control devices such as screw propellers, rudders, azimuth propellers, thrusters.

Most of contemporary DP ship control methods are based on equations of mathematical model of object kinematics and dynamics [9, 22, 28]. Changes in point of operation of the system and impact of hydrodynamic phenomena result in that the ship kinematics and dynamics equations contain nonlinearities as well as variable coefficients.

Control over nonlinear systems with uncertainties still constitutes rather a not recognized field. The adaptive control method such as disturbance rejection control (ADSC), backstepping [10, 24, 25] as well as its modifications either of DSC (dynamic surface control) type [20, 26, 27] or other adaptive methods based on artificial intelligence theory [1, 3, 12, 16], make it possible to design a dynamically varying feedback loop. The fundamental idea of the adaptive designing of control rule consists first of all in the assessing of value of an unknown parameter as well as the determining of its estimate. Next, the static part of the controller which contains estimated parameters is continuously actualized, depending on varying operational conditions of the system.

From the point of view of adaptive controller resistance analysis, information as to the impact of model parametric uncertainties on to control quality of the system, is crucial. In order to determine the impact of parameters of a multi-parameter model on dynamic properties of control system there can be used a. o. numerical methods such as Monte Carlo [27, 28], or Pareto [29] approach as well as artificial intelligence methods, which facilitate assessment of imprecise values as well as their interpretation in case of uncertain data [5, 21]. In the classic Monte Carlo method, the susceptibility of the system is subject to assessing in the situation when all parameters deviate from their nominal values simultaneously. By applying Pareto rule the system is subject to quality analysis. For an assumed variability range of estimated parameters, classification is performed and an impact of particular system parameters on value of objective function is determined.

An original contribution of this work to the considered question is determination of linguistic variables characterizing susceptibility of model parameters as well as determination of their affiliation to appropriate sets which define either crucial, moderate or minimum impact of the parameters on objective function. For this reason, there was carried out a susceptibility analysis of changes in values of control quality index for the ship dynamic positioning system designed with the application of the backstepping adaptive controller [10, 24, 6]. Such system was already proposed by these authors in the paper [25].

In this work simulation investigations on the susceptibility of the system were performed with taking into account the integral control quality index. The assessment of the impact of model parameters on to control quality index was made on the basis of Pareto-Lorentz curves. During designing the control rule there were assumed that parametric uncertainties of damping matrix, Coriolis forces and environmental disturbances, may appear. The RBF neural network [2, 4, 18] was applied in every instant to approximate nonlinear functions containing parametric uncertainties. Rules for network's weights adaptation were determined with the use of Lapunov stability theory, depending on a point of operation of the system. Owing to this the neural network does not require any initial process of tuning the weights off-line.

STRUCTURE OF CONTROL SYSTEM

As far as the multi-layer structure of DP ship control is concerned, two control loops are of interest: the open feedforward loop where coupling signal is generated by the block of disturbance modelling (model of wind) as well as the main feedback control loop where set values of ship position and heading (course angle) are compared with their estimated values. The feedback control loop interacts with the control block directly, the drive control allocation system and measuring systems as well as the systems for ship position and heading estimation. The main control loop (Fig. 1) consists of the following modules: position and heading controller with control allocation system, dynamics of propellers, dynamics of DP ship (controlled object), and the observer of current estimated output values of position, heading and speed components: longitudinal, transverse and angular.

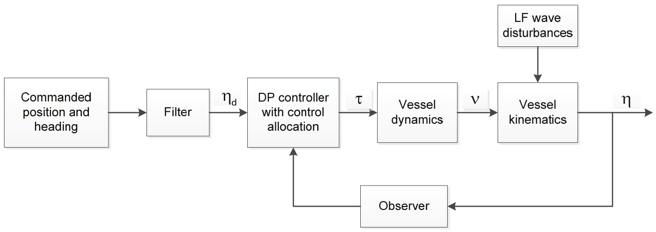

Fig. 1 Structure of DP control system

Based on comparison of the vector of set values of position and heading, $\boldsymbol{\eta}_d$, with the vector of currently estimated values achieved from the observer, the DP controller determines forces and moments necessary to compensate deviations from the set values, in accordance with an assumed value of control error. In this system the DP controller of ship position and heading controls independently motion of the object in three degrees of freedom, determining: set values, the generalized vector of longitudinal and transverse forces and torsion moment for drive control allocation system where distribution of forces to appropriate settings of actuators is performed.

The system based on adaptive model of object, in this case – a ship, contains hydrodynamic description of its dynamic features and makes it possible to determine estimated values of parameters of position and heading. The model describes object's motion and response, with taking into account variable characteristics of resistance and added mass coefficients, depending on acting forces and moments.

MATHEMATICAL MODEL OF DP SHIP

During designing the control rule based on backstepping method and artificial neuronal networks, the mathematical model of motion of a unit dynamically positioned in horizontal plane, described by the following set of differential equations, was assumed [7]:

$$\dot{\boldsymbol{\eta}} = \mathbf{J}(\boldsymbol{\eta})\mathbf{v} \quad (1)$$

$$\mathbf{M}(\mathbf{v})\dot{\mathbf{v}} = \boldsymbol{\tau} + \mathbf{J}(\boldsymbol{\eta})^T\mathbf{b} - \mathbf{D}(\mathbf{v})\mathbf{v} - \mathbf{C}(\mathbf{v})\mathbf{v} \quad (2)$$

where: $\boldsymbol{\tau} = [\tau_x, \tau_y, \tau_z]^T$ – generalized vector of forces and moments acting on the ship, $\boldsymbol{\tau}=[x, y, \psi]^T$ – vector of ship position and heading, $\mathbf{v} = [u, -v, r]^T$ – vector of longitudinal, transverse and angular components of ship speed; the matrices $\mathbf{M} \in R^{3\times3}$, $\mathbf{D} \in R^{3\times3}$ i $\mathbf{C} \in R^{3\times3}$, $\mathbf{J}(\boldsymbol{\eta}) \in R^{3\times3}$ define respectively:

Inertia matrix

$$\mathbf{M} = \begin{bmatrix} m_{11} & 0 & 0 \\ 0 & m_{22} & m_{23} \\ 0 & m_{32} & m_{33} \end{bmatrix}$$

Damping matrix

$$\mathbf{D} = \begin{bmatrix} d_{11} & 0 & 0 \\ 0 & d_{22} & d_{23} \\ 0 & d_{32} & d_{33} \end{bmatrix}$$

Matrix of Coriolis forces

$$\mathbf{C}(\mathbf{v}) = \begin{bmatrix} 0 & 0 & c_1 v + c_2 r \\ 0 & 0 & c_3 u\text{“} \\ -c_1 v\text{“}\text{-}c_2 r\text{“} & -c_3 u\text{“} & 0 \end{bmatrix}$$

and the transformation matrix (dependent on state variables) of ship's gravity centre coordinates into the Earth-fixed coordinate frame:

$$\mathbf{J}(\boldsymbol{\eta}) = \begin{bmatrix} cos\psi & -sin\psi & 0 \\ sin\psi & cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

The vector $\mathbf{b} = [b_1, b_2, b_3]^T$ represents non-modelled, slow-varying environmental disturbances. The ship's model takes into account 3DOF motion, namely: longitudinal motion, transverse motion and change in bow heading angle.

The equation system (1)-(2) is of a cascade structure. The vector $\boldsymbol{\tau}$ constitutes the control input to the system, while the vector $\mathbf{v}$ is a "virtual controllable output ". It simultaneously serves as a „virtual control input" for the subsystem (1). The vector of ship's position and heading, $\boldsymbol{\eta}$, is the controllable output from the whole system.

During designing the control rule there was assumed that the ship's dynamics model contains parametric uncertainties in the matrices **D, C, M**, and that components of the vector **b** are unknown but slow-varying. Moreover, there was assumed that all state variables are measurable (or estimated) and limited. The set trajectories of position and heading, $\boldsymbol{\eta}_d = [x_d, y_d, \psi_d]^T$ as well as their derivatives of 1st and 2nd order are smooth and time – limited functions.

DP CONTROLLER

According to the backstepping method, for the system (1)-(2) there were defined new state variables in the form of the control errors $\mathbf{z}_1(t) \in R^{3\times1}$ and $\mathbf{z}_2(t) \in R^{3\times1}$ as well as the vector of functions for stabilizing the first subsystem, $\boldsymbol{\alpha} \in R^{3\times1}$. In the ship-fixed coordinate frame the control errors take the following form:

$$\mathbf{z}_1 = \mathbf{J}(\boldsymbol{\eta})^T(\boldsymbol{\eta} - \boldsymbol{\eta}_\mathrm{d}) \quad (3)$$

$$\mathbf{z}_2 = \mathbf{v} - \boldsymbol{\alpha} \quad (4)$$

And, the stabilizing functions vector will be determined during designing the control rule. Based on the model kinematics and dynamics equations (1)-(2), derivatives of the control errors were determined as follows [25]:

$$\dot{\mathbf{z}}_1 = -r\mathbf{S}\mathbf{z}_1 + \mathbf{z}_2 + \boldsymbol{\alpha} - \mathbf{J}(\boldsymbol{\eta})^T\dot{\boldsymbol{\eta}}_d \quad (5)$$

$$\mathbf{M}\dot{\mathbf{z}}_2 = \boldsymbol{\tau} + \boldsymbol{f}(\boldsymbol{\eta}, \mathbf{v}, \boldsymbol{\eta}_d, \mathbf{v}_d) \quad (6)$$

After denoting the state variables dependent matrix by: $\mathbf{X} = [\boldsymbol{\eta}, \mathbf{v}, \boldsymbol{\eta}_d, \mathbf{v}_d]$, the function $\boldsymbol{f} \in R^{3x1}$ takes the following form:

$$\boldsymbol{f}(\mathbf{X}) = -\mathbf{C}\mathbf{v} - \mathbf{D}\mathbf{v} + \mathbf{J}(\boldsymbol{\eta})^T\mathbf{b} - \mathbf{M}\dot{\boldsymbol{\alpha}} \quad (7)$$

which contains unknown model parameters.

In order to determine the adaptation rule for the parameters of the matrices **M, D, C** and the vector **b** it is necessary to represent the function $\boldsymbol{f}$ in the form of a regression model and proceed further in compliance with the backstepping procedure. The components of the function $\boldsymbol{f} = [f_1, f_2, f_3]^T$ were approximated by three artificial neural networks NN_i of RBF type [25] whose outputs $\hat{\boldsymbol{f}} = [\hat{f}_1, \hat{f}_2, \hat{f}_3]^T$ were defined in the form of the following regression model:

$$\hat{f}_i(\mathbf{X}_i) = \boldsymbol{\varphi}_i^T(\mathbf{X}_i)\boldsymbol{\theta}_i;\ i = 1..3 \quad (8)$$

In the proposed system the number of radialneurons $l = 4$ was determined experimentally.

The input vector for neural network is as follows: $\mathbf{X}_i = [\boldsymbol{\eta}(i), \mathbf{v}(i), \boldsymbol{\eta}_d(i), \mathbf{v}_d(i)]^T \in R^{4x1}$, and the set of values of basis functions of the networks NN_i: $\boldsymbol{\varphi}_i = [\boldsymbol{\varphi}_{i1}, \boldsymbol{\varphi}_{i2}, \dots, \boldsymbol{\varphi}_{il}]^T \in R^{lx1}$. Selection of the weights $\boldsymbol{\theta}_i = [\boldsymbol{\theta}_{i1}, \boldsymbol{\theta}_{i2}, \dots, \boldsymbol{\theta}_{il}]^T \in R^{lx1}$ was made during the process of the control system adaptation to varying operational conditions.

The control error dynamics equation (6) supplemented with RBF network equation, takes the following form:

$$\mathbf{M}\dot{\mathbf{z}}_2 = \boldsymbol{\tau} + \boldsymbol{\varphi}^T(X)\boldsymbol{\theta} \tag{9}$$

The regression vector, i. e. the vector of RBF network weights, is defined to be: $\boldsymbol{\theta}=[\boldsymbol{\theta}_1^T, \boldsymbol{\theta}_2^T, \boldsymbol{\theta}_3^T]^T \in R^{3lx1}$. And, the regression matrix $\boldsymbol{\varphi}^T \in R^{3x3l}$ is expressed as follows:

$$\boldsymbol{\varphi}^T = \begin{bmatrix} \boldsymbol{\varphi}_1{}^T(X) & \mathbf{0}_{1xl} & \mathbf{0}_{1xl} \\ \mathbf{0}_{1xl} & \boldsymbol{\varphi}_2{}^T(X) & \mathbf{0}_{1xl} \\ \mathbf{0}_{1xl} & \mathbf{0}_{1xl} & \boldsymbol{\varphi}_3{}^T(X) \end{bmatrix} \tag{10}$$

The task for the backstepping controller is to determine the indirect control rule $\boldsymbol{\alpha}$ intended for stabilizing the first subsystem (1), next the control rule $\boldsymbol{\tau}$ for stabilizing the entire system (1)-(2) as well as the adaptation rule for the vector of weights $\boldsymbol{\theta}$, in relation to Lapunov function of the system.

The control rule was determined in relation to the Lapunov function $\boldsymbol{V}_\alpha$ which is a sum of squares of control errors and a component associated with estimation error of an unknown vector of weights $\boldsymbol{\theta}$.

$$\mathbf{V}_a = \frac{1}{2}\mathbf{z}_1^T\mathbf{z}_1 + \frac{1}{2}\mathbf{z}_2^T\mathbf{M}\mathbf{z}_2 + \frac{1}{2}\tilde{\boldsymbol{\theta}}^T\boldsymbol{\Gamma}^{-1}\tilde{\boldsymbol{\theta}} \tag{11}$$

where: $\boldsymbol{\Gamma} > 0$ is the diagonal matrix of controller amplifications, $\dim\boldsymbol{\Gamma} = 3l \text{ x } 3l$, $\tilde{\boldsymbol{\theta}}$ – the vector of estimation errors.

The control rules, $\boldsymbol{\alpha}$, $\boldsymbol{\tau}$ are so selected as the Lapunov function derivative (12) to be negatively half-determined in the new variables system:

$$\dot{\mathbf{V}}_a = -\mathbf{z}_1^T\mathbf{K}_1\mathbf{z}_1 - \mathbf{z}_2^T\mathbf{K}_2\mathbf{z}_2 \le \mathbf{0} \tag{12}$$

And, $\mathbf{K}_j \in R^{3x3}$, $j = \{1,2\}$, represents the control amplifications matrix which is diagonal and positively determined. Comparing the derivative of the function (11) with the expression (12) one is able to determine the following relations:

- Adaptation mechanism for weights:

$$\dot{\hat{\boldsymbol{\theta}}} = \boldsymbol{\Gamma}\boldsymbol{\varphi}(\mathbf{X})\mathbf{z}_2 \tag{13}$$

- Vector of stabilizing functions $\boldsymbol{\alpha}$, independent of the vector of estimates $\hat{\boldsymbol{\theta}}$:

$$\boldsymbol{\alpha} = -\mathbf{K}_1\mathbf{z}_1 + \mathbf{J}(\boldsymbol{\eta})^T\dot{\boldsymbol{\eta}}_d \tag{14}$$

- Vector of control settings $\boldsymbol{\tau}$, dependent on the vector of estimates $\hat{\boldsymbol{\theta}}$ (weights of RBF network), calculated in accordance with (13), under assumption that the network posesses a sufficient number of neurons:

$$\boldsymbol{\tau} = -\mathbf{K}_2\mathbf{z}_2 - \mathbf{z}_1 - \boldsymbol{\varphi}^T(X)\hat{\boldsymbol{\theta}} \tag{15}$$

If in the system fast varying disturbances do not act then the control rule (15) together with the adaptation rule (13) ensures asymptotic convergence of ship position and heading towards their set values, $\boldsymbol{\eta}(t) \to \boldsymbol{\eta}_d(t)$, at $\mathbf{v}(t) \approx 0$. It also ensures limited changes in the signals $\boldsymbol{\eta}(t)$ i $\mathbf{v}(t)$, $t \to \infty$, at a limited change in values of estimated parameters.

DESCRIPTION OF THE METHOD

For the investigations of impact of ship model parameters on control system quality, the integral quality index J defined to be a sum of squares of control deviations, was assumed:

$$J = \int_{t_0}^{t_n}((x - x_d)^2 + (y - y_d)^2 + (\psi - \psi_d)^2)dt \tag{16}$$

The quality of the control system designed on the basis of ship's mathematical model is affected a.o. by errors resulting from non-exact information on the model parameters, i.e. coefficients of the matrices **M**, **C**, **D** and **b.** Applying the procedure described in [29], one determined a set of basis parameters whose impact on objective function is investigated. Next, for every basis parameter p_i, $i \in \{1,..,n\}$ its variability interval was assumed as follows:

$$p_{imin} < p_i < p_{imax}$$

For the analyzing of impact of particular parameters on value of the objective function J_i in the form of (17):

$$J_i = \frac{|J_{imax} - J_{imin}|}{J_{imax}}, \quad i \in \{1,..,n\} \tag{17}$$

where: $J_{imax} - J_{imin}$ is the difference between maximum and minimum value of the objective function J_i determined for the assumed parameter variability interval p_i, the coefficient w_i corresponding to the parameter p_i was determined, depending on value of the evaluation function (17):

$$w_i = \frac{J_i}{\sum_i J_i}, \quad i \in \{1,..,n\} \tag{18}$$

The coefficient w_i determines a degree of effect of the parameter p_i on evaluation value with respect to the entire set of parameters. After performing the calculations for all parameters one obtains a relative summary value of the the coefficients w_i (18), i. e. the cumulated value S_i:

$$S_i = \sum_{k=1}^{i} w_k = 1 \text{ of the property: } S_n = 1 \tag{19}$$

Based on the obtained values, Pareto-Lorentz curves illustrating a share of each parameter p_i are formed. On the basis of Lorentz curve there is possible to classify the parameters, i.e. to determine affiliation of the parameters to the sets A, B, C, which have crucial, moderate and minimum impact on values of objective function, respectively. To this end, a classification typical for the classic ABC method was used to affiliate parameters: to the set A when values of their cumulated sums S_i were lower than 80%, to the set B when they were comprised within the range <80%, 95%), and to the set C – when over 95%. The above presented analysis was carried out for the set points of the control system operation. Below are presented results of the analysis of basis parameters impact on value of objective function for various changes in values of set ship positions and headings.

SIMULATION INVESTIGATIONS

During ship manoeuvring ship's model parameters vary along with time, depending on many factors, a.o. hydrodynamic coefficients and ship speed. Model errors associated with parametric uncertainties have significant impact on deviation of ship's real trajectory from that assumed. In the analysis of impact of model uncertainties on dynamic features of the control system both quantitative and qualitative methods are used. In the publications [8, 13] Monte Carlo simulations were implemented for quantitative determination of uncertainties in DP system. In this work the authors' attention was focussed on qualitative analysis consisting in application of ABC method and Pareto-Lorentz curves to determine impact of particular parameters on changes in control quality index. The knowledge gained this way may be directly used for tuning the adaptive control system by taking into account range of each of the parameters. Such method has not been so far applied to susceptibility investigations of DP adaptive control system.

For the simulation investigations a mathematical model of a supply ship of L=76.2m in length and 4591 t mass, was selected. The real dimensionless parameters of the model (1)-(2) were determined by using the Bis scaling system [7] and presented in Tab. 1. In the tests in question tere were selected zero-initial values of position and heading and estimated weights. During the tests with adaptive controller there were considered programmable inertial changes in values of the set longitudinal and transveres position, resulting from occurrence of slow-varying environmental disturbances modelled with the use of Markov process [7]. The parameters presented in Tab.1 are the model basis parameters whose variability range equal to ±20% of their real value was assumed.

Tab.1. Dimensionless values of basis parameters (Bis – scaled)

i	Parameter p_i	Value
1	c_1	-1,8902
2	c_4	-1,1274
3	d_{32}	-0,1073
4	$m_{23}\, m_{32}$	-0,0744
5	d_{23}	-0,0141
6	d_{11}	0,0414
7	d_{33}	0,0568
8	c_2	0,0744
9	m_{33}	0,1278
10	d_{22}	0,1775
11	m_{11}, c_3	1,1274
12	m_{22}	1,8902

Three cases of change in values of set position and heading were considered: for, $\boldsymbol{\eta}_d$ = (10,10,10), $\boldsymbol{\eta}_d$ = (5,10,10) and $\boldsymbol{\eta}_d$ = (10,5,10).

First of all, for the assumed range of changes in basis parameters (Tab. 1) and $\boldsymbol{\eta}_d$ = (10,10,10) relative values of the quality index J_i (17), coefficients w_i (18) as well as values of the cumulated sum S_i (19) (Tab. 2) were determined.

Tab. 2. List of relative values of the quality index J_i, coefficients w_i and values of the cumulated sum S_i, for $\boldsymbol{\eta}_d$ = (10,10,10)

i	J_i	w_i	S_i
10	0,530871367	2,81E-03	0,50492
3	0,153670167	2,97E-03	0,651078
7	0,121097925	1,46E-01	0,766257
5	0,081978813	4,42E-03	0,844228
12	0,074335195	7,80E-02	0,914929
11	0,046881248	2,99E-02	0,959519
6	0,031399883	1,15E-01	0,989384
4	0,004646388	8,75E-05	0,993803
2	0,003126372	3,29E-04	0,996777
1	0,002951551	5,05E-01	0,999584
9	0,000345541	4,46E-02	0,999912
8	9,20E-05	7,07E-02	1

Applying the ABC rule one is able to conclude that the parameters: d_{22}, d_{32}, d_{33} constitute the group A which has crucial impact on control quality in the tested system. The parameters, d_{23}, m_{22} have moderate impact (group B). And, the remaining basis parameters are of a minimum impact on control quality in the tested system hence they belong to the group C.

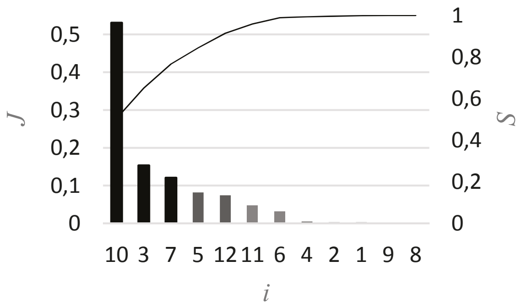

Fig. 2 Pareto-Lorentz diagram which takes into account relations between parameters, their relative values of control quality index J as well cumulated values S, determined for η_d = (10,10,10)

Fig. 3 presents both the desired and real ship's trajectories for the case η_d = (10,10,10), with taking into account the parameters belonging to the group A. The diagrams were depicted for changes in values of the parameters equal to ±20% of their respective real values.

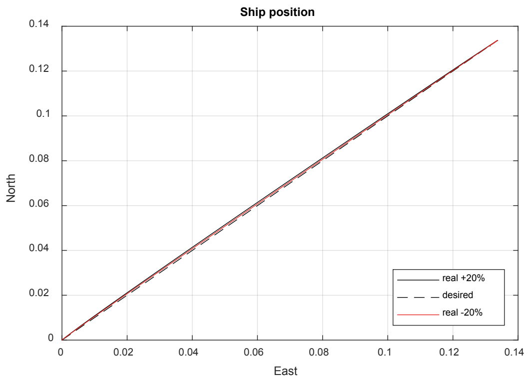

Fig. 3 Diagram of the desired ship's trajectory and real ones for the case: η_d = (10,10,10) with taking into account ±20% change in values of the parameters of the group A

In an analogous way, for η_d = (5,10,10) there were determined the groups of basis parameters of crucial (A), moderate (B) and minimum (C) impact on control quality in the tested system.

The obtained values are listed in Tab. 3 and presented in the form of Pareto-Lorentz diagram (Fig. 4).

Tab. 3. List of relative values of the quality index J_i, coefficients w_i and values of the cumulated sum S_i, for η_d = (5,10,10)

i	Ji	w_i	S_i
10	0,528009734	0,546174556	0,528009734
3	0,163289371	0,168906923	0,691299105
7	0,123589817	0,127841608	0,814888923
5	0,079851728	0,082598822	0,894740651
12	0,074719631	0,077290169	0,969460282
11	0,015337254	0,015864893	0,984797536
6	0,007303802	0,007555071	0,992101338
4	0,004359707	0,004509692	0,996461045
2	0,001745608	0,001805662	0,998206654
1	0,001311787	0,001356916	0,999518441
9	0,000468859	0,000484989	0,9999873
8	1,26998E-05	1,31367E-05	1

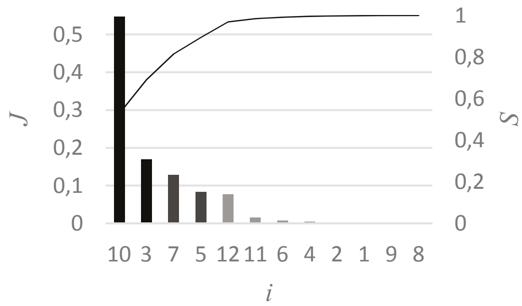

Fig. 4. Pareto-Lorentz diagram which takes into account relations between parameters p_i, their relative values of control quality index J_i as well cumulated values S_i, determined for η_d = (5,10,10)

It was observed that in the case of η_d = (5,10,10), only the parameters d_{22}, d_{32} belong to the group A,i.e. that of crucial impact on control quality in the investigated system, and only, d_{33}, d_{23} – to the group B of a moderate impact. The remaining parameters exert a minimum impact,hence they may be numbered among elements of the group C.

The simulation investigations were conducted also for the third case: η_d = (10,5,10).

The obtained values are collected in Tab. 4 and presented graphically in Fig. 5.

Tab. 4. List of relative values of the quality index J_i, coefficients w_i and values of the cumulated sum S_i, for η_d = (10,5,10)

i	J_i	w_i	S_i
10	0,484719261	0,412553523	0,412553523
11	0,179230742	0,152546598	0,565100121
6	0,151323221	0,12879399	0,693894112
5	0,150468087	0,12806617	0,821960282
12	0,087428568	0,07441207	0,896372352
7	0,061862607	0,052652409	0,949024761
3	0,038088145	0,032417524	0,981442284
4	0,012550981	0,010682372	0,992124656
1	0,007055257	0,00600486	0,998129516
9	0,0007843	0,000667532	0,998797048
2	0,000718445	0,000611482	0,99940853
8	0,000694933	0,00059147	1

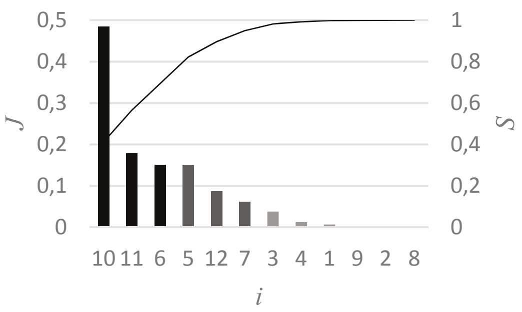

Fig. 5 Pareto-Lorentz diagram which takes into account relations between parameters p_i, their relative values of control quality index J_i as well as the cumulated values S_i, determined for $\boldsymbol{\eta}_d$ = (10,5,10)

The performed simulation investigations made it possible to determine impact of the parameters on control quality index in the tested system, taking into account: $\boldsymbol{\eta}_d$ = (10,10,10), $\boldsymbol{\eta}_d$ = (5,10,10) and $\boldsymbol{\eta}_d$ = (10,5,10), and as well as changes in values of the basis parameters, ranging ±20% of their real values. The parameters were assigned to particular groups in accordance with ABC method (Tab. 5)

Tab. 5. List of basis parameters and their affiliation to particular groups of their significance in the process of the tested system control during successive simulations with taking into account the set values: $\boldsymbol{\eta}_d$ = (10,10,10), $\boldsymbol{\eta}_d$ = (5,10,10) and $\boldsymbol{\eta}_d$ = (10,5,10)

i	(10,10,10)	(5,10,10)	(10,5,10)
1	C	C	C
2	C	C	C
3	A	A	C
4	C	C	C
5	B	B	B
6	C	C	A
7	A	B	B
8	C	C	C
9	C	C	C
10	A	A	A
11	C	C	A
12	B	C	B

In view of a lack of an unambiguous affiliation of the parameters to particular ABC groups in various points of the system operation, the obtained results were properly averaged. Namely, by making use of the relations (17 – 19), the average values of the coefficients J_i, w_i, S_i, were calculated, as presented in Tab. 6. This made it possible to classify again the parameters to particular groups. Now, to the group A belong the parameters: d_{22}, d_{32}, d_{23}, and to the group B: m_{22}, m_{11}, c_3. The remaining ones are of a minimum impact hence they may be assigned to the group C.

Tab. 6. List of relative values of the quality index J_i, coefficients w_i and values of the cumulated sum S_i, – averaged values obtained from all simulations

i	J_i	w_i	S_i	Group
1	0,003773	0,003508	0,997524	C
2	0,001863	0,001733	0,999257	C
3	0,118349	0,110047	0,588487	A
4	0,007186	0,006682	0,994016	C
5	0,1041	0,096797	0,685284	A
6	0,063342	0,058899	0,987334	C
7	0,102183	0,095015	0,7803	A
8	0,000267	0,000248	1	C
9	0,000533	0,000496	0,999752	C
10	0,514533	0,47844	0,47844	A
11	0,080483	0,074837	0,855137	B
12	0,078828	0,073298	0,928435	B

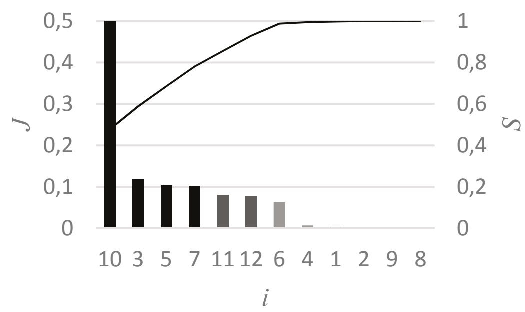

Fig. 6. Pareto-Lorentz diagram which takes into account relations between parameters p_i, relative values of control quality index J_i as well as the cumulated values S_i, obtained during all simulations

The computer simulation results show that the system behaves correctly within the tested range of changes in estimated parameters, amounting to ± 20% of their respective real value, as well as for the assumed level of disturbances.

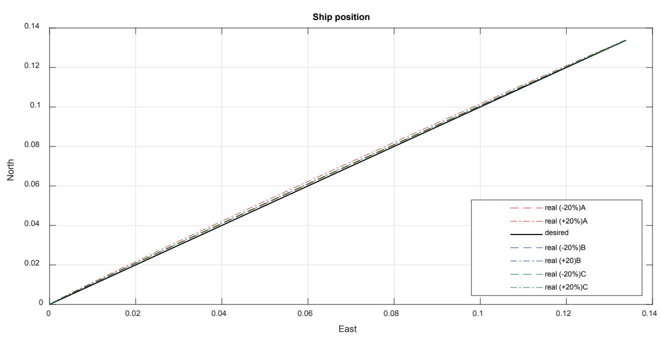

Fig. 7. The desired and real trajectory of the ship for $\boldsymbol{\eta}_d$ = (10,10,10) and ±20% change in averaged values of the parameters classified to the groups A, B, C, respectively

For the parameters of crucial impact on values of the control quality index the ship's position deviations from the desired trajectory (Fig. 7) can be observed. Therefore it can be stated that the tested control system is more susceptible to changes in values of the parameters belonging to the group A, but less susceptible to model inaccuracies resulting from changes in values of the parameters of the groups B and C.

CONCLUSIONS

In this work there was performed a qualitative analysis of the designed DP ship control system with adaptive backstepping controller and RBF neural network used for estimation of ship model nonlinear function.

The qualitative analysis of the system conducted by means of Pareto-Lorentz diagrams and ABC method made it possible to distinguish which model parameters have crucial, moderate or minimum impact on changes in values of the control quality index.

It was observed that, depending on change in set values of ship position and heading, particular ABC groups contained another set of parameters. It means that each parameter affects the tested system to a different degree. In this case the concluding process based on classic methods may appear imprecise. In the future the investigated system may be tested towards finding its behaviour in function of its operational point with the use of fuzzy sets logic. In the case of multi-parameter adaptive systems, information about impact of model parameters on changes in values of the control quality index may be used for tuning the control system and may effectively simplify analysis of the system resistance against modelling errors.

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