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A simple technique for identifying vessel model parameters

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Abstract. The marine autopilot system design is based on the mathematical model of steering dynamics. Ships maneuvering can be automated by using the autopilot system. A simple method for identifying the parameters of the ship's mathematical model is presented. In the present paper a study on Nomoto model has been undertaken for its selection for the ships steering dynamics. To identify the parameters of the ship model it is proposed to use: a) the results of «zigzag» tests; b) process the result of the tests using the Fourier transform. Next, a system of equations for 1, 3, 5 and so on harmonics of the Nomoto transfer function is compiled. The solution of the system allows us to find the time constants and the coefficients of the model. Verification of the results was carried out on the basis of «reverse» modeling.

The need to improve maritime safety and operational characteristics of marine vessels has led to the creation of different types of autopilots. Modern autopilots provide not only effective stabilization of the course of the vessel, but also self-tuning parameters of the course management system with changes in the condition of the vessel (draught, type of cargo) and sailing conditions (speed, weather, depth). The result is stabilization of the vessel at a predetermined rate with a minimum power loss of ship power plants (SPP) for handling (loss of yaw).

Such systems of autopilot steering control system (ASCS) allow to reduce the loss of running time by 3–4 %, increase the carrying capacity of the vessel and reduce fuel consumption for the flight by 3–6 %. The operation of any of the (ASCS) is based on a mathematical model for the dynamics of steering a ship [1–5]. Naturally, the more accurate the mathematical model will describe the real conditions of the vessel's motion, the more effectively it is possible to synthesize the (ASCS), the less resulting losses of the vessel's power plant [5–8].

Currently, the theory of control of the ship is fairly well developed and allows to build adequate physical processes of the movement of the ship mathematical model. The mathematical model of the vessel is usually based on six degrees of freedom of motion of a rigid body in space. However, the control system synthesized based on such model (control controllers) turns out to be cumbersome, in many respects - excessive and unreasonably sharply reacting to rapidly changing external influences. The compromise between the complexity of the mathematical model and the adequacy of the model to real physical processes led to the development of simplified mathematical descriptions of the vessel's motion.

The IMO (International Maritime Organization) has developed and adopted resolution A. 751(18), which regulates the need to use mathematical models of the vessel in solving practical problems in the field of navigation safety. As a result of the application of resolution A. 751(18), simplified mathematical models of Nomoto ship-models of the first and second orders of magnitude were recommended for practical use at several international conferences of experimental basins (e.g. the 14th conference) [9–11]. The first-order Nomoto model is extremely simplified and is often used for verification (evaluation, preliminary) calculations.

The second-order Nomoto model [10, 11] is more efficient in practice and is described by the differential equation:

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$$T_1 \cdot T_2(d^2\omega/dt^2) + (T_1+T_2)(d\omega/dt) + \omega + H(\omega) = K\cdot\alpha_r + KT_3(d\alpha_r/dt), \qquad (1)$$

where ω – angular frequency (speed) of the vessel; $H(\omega) = \nu_1|\omega|\omega + \nu_2\omega^3$ – the nonlinear function of the angular frequency; T_1, T_2, T_3, K, ν_1, ν_2 – the parameters of the mathematical model; α_r – rudder angle.

The practical use of such a model (synthesis of control controllers for the course stabilization system) is extremely difficult due to the need to know for a particular vessel the basic parameters of the model (1): T_1, T_2, T_3, K, ν_1, ν_2.

One of the simple solutions to this problem of parameter identification of equation (1) is presented in the following material.

To identification of parameters of different mathematical models of the vessel, including-non-linear model (1) Nomoto, is devoted a very large number of publications, for example, [12–15]. This confirms the importance and relevance of studies related to the identification of Nomoto model parameters. Analysis of these [12–15] and other [16, 17] publications shows that the authors of the research use a variety of experimental data and a diverse mathematical apparatus of identification. These are statistical analysis, neuro-fuzzy identification and modelling, decomposition into periodic functions, approximation of various types and many other methods.

In resolutions IMO A. 160(ES.IV), A. 209(VII), A. 609(15) is mentioned the need to provide each of the vessels with objective data on their manoeuvrability characteristics. IMO resolution A. 751(18) specifically recommends the use to ensure safe navigation and build control systems for manoeuvring parameters such qualities as agility, risk level, stability on the course, braking performance [9]. Manoeuvrability qualities are determined for each vessel, mainly experimentally, and all the main test results are found in the vessel's manufacturer and in the ship's documentation.

It is this fact that the test results available on each vessel (or vessel of a similar design), such as the steady-state frequency of circulation and the «zigzag 10-10» or the «zigzag 20-20» [12–17], can be used.

Let us consider there are two experimental characteristics:

a) the static dependence of the steady-state angular frequency of circulations ω in the function of the rudder angle α_r (diagram of controllability, Fig. 1);

b) the results of the «zigzag» manoeuvre test (Fig. 2). Note that such features may be produced in the testing tank pool - with a small copy of the ship, or using a full-scale, taking into account the hydrodynamics of the vessel simulation.

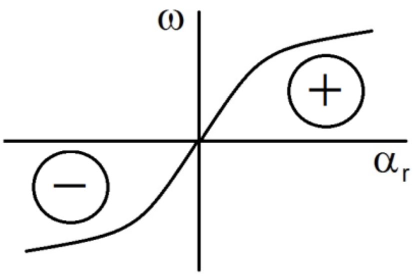

Figure 1. Manageability chart

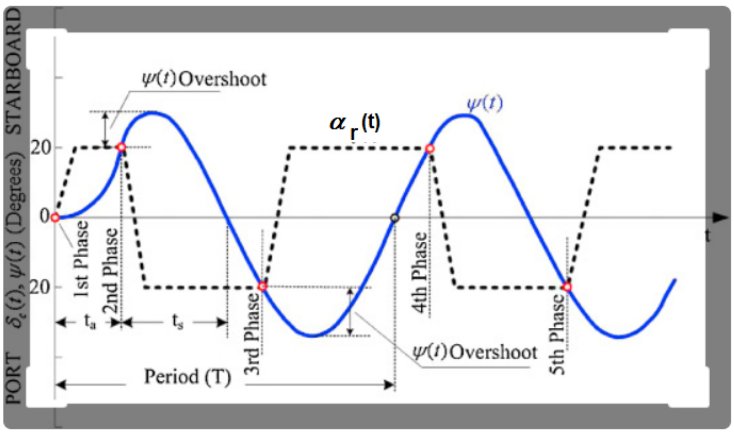

Figure 2. Figure «zigzag»

From the analysis of equation (1) shows that in the static mode (dω/dt = 0) we can write the equation $\nu_1|\omega_i|\omega_i + \nu_2\omega_i^3 + \omega_i = K\cdot\alpha_{ri}$, and for the positive circulation (Fig. 1) to obtain the expression:

$$\nu_2\omega_i^3 + \nu_1\omega_i^2 + \omega = K\alpha_{ri} \qquad (2)$$

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Dividing the expression (2) to a work ($\omega_i \cdot K$), we get

$$\nu_2\omega_i^2 / K + \nu_1\omega_i / K + 1/K = \alpha_{ri} / \omega_i. \tag{3}$$

Substituting in (3) a few different values of the frequency ω_i for the respective angles of the rudder, for example, 2, 4, 6, ..., 30 degrees, we obtain a system of n-linear algebraic equations with three unknowns ν_2/K, ν_1/K and 1/K, and n > 3.

It is an overridden, redundant, system (RF – Redefined System or OS – Overdetermined System) and it does not have an exact classic solution. Known quasi-solution of the over determined systems of various kinds. For example, one of the possible solutions is based on the least squares method - Lagrange method [18, 19]. The result of such a decision may be some approximating expression. The graphical solution is a curve that does not pass through the experimental points of the steady-state angular frequency of circulations ω_i in the steering angle function α_r. It should be emphasized that at the same time the solution based on [18, 19] fully reflects the experimental dependence presented in Fig. 1, smoothing the errors (emissions, noises) of the experiment.

Thus, we find three unknown parameters of the equation (1) – K, ν_1, ν_2. It is necessary to find three more time constants T_1, T_2 and T_3. We will assess the required time constants in the following way.

We analyse the type of experimental dependence «zigzag» (Fig. 2) – dependence of the heading angle ψ function of the rudder angle α_r. It can be noted that for the steady state mode (excluding the first oscillations) both dependences are nonlinear, periodic and practically symmetrical with respect to the time axis.

We use the Fourier series decomposition method of the input α_r and output ψ signals to identify the three time constants. To do this, assign the main period T = 1/ω_1, based on the schedule shown in (Fig. 2). We limit ourselves to the first three odd harmonics of the decomposition: the first (main), the third and the fifth.

Because of series decomposition, we obtain three harmonics for the input signal. Each of the harmonics will be characterized by the amplitude $A_{1r}(\omega_1)$, $A_{3r}(\omega_3)$ и $A_{5r}(\omega_5)$ and phase $\varphi_{1r}(\omega_1)$, $\varphi_{3r}(\omega_3)$, and $\varphi_{5r}(\omega_5)$ for the respective frequencies ω_1, $\omega_3 = 3\omega_1$ и $\omega_5 = 5\omega_1$. By analogy, the decomposition obtained for the output signal values of the amplitude $B_{1\Psi}(\omega_1)$, $B_{3\Psi}(\omega_3)$ and $B_{5\Psi}(\omega_5)$, phases – $\varphi_{1\Psi}(\omega_1)$, $\varphi_{3\Psi}(\omega_3)$ and $\varphi_{5\Psi}(\omega_5)$.

Then the complex values of the transmission coefficients for each harmonic can be recorded (omitting to simplify the recording $\omega_{1,3,5}$) as the ratio of the output to the input signal:

$$\left.\begin{aligned} K_1 \cdot e^{j\alpha_1} &= \frac{B_{1\Psi}}{A_{1r}} \cdot e^{j(\varphi_{1\Psi} - \varphi_{1r})}; \\ K_3 \cdot e^{j\alpha_3} &= \frac{B_{3\Psi}}{A_{3r}} \cdot e^{j(\varphi_{3\Psi} - \varphi_{3r})}; \\ K_5 \cdot e^{j\alpha_5} &= \frac{B_{5\Psi}}{A_{5r}} \cdot e^{j(\varphi_{5\Psi} - \varphi_{5r})}. \end{aligned}\right\}. \tag{4}$$

For the regime of small deviations can be neglected in (1) the nonlinear term H(ω). Then get:

$$T_1 \cdot T_2(d^2\omega/dt^2) + (T_1 + T_2)(d\omega/dt) + \omega = K \cdot \alpha_r + KT_3(d\alpha_r/dt). \tag{5}$$

The transfer function corresponding to the expression (5) will look like:

$$W(s) = \frac{\omega(s)}{\alpha_r(s)} = \frac{(T_3 s + 1)}{(T_1 s + 1)(T_2 s + 1)}. \tag{6}$$

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It is obvious that after the transition to the frequency domain (making a formal replacement $s = j\omega$), it is easy to write down from y (4) and (6) a system of three equations with three unknowns T_1, T_2 and T_3:

$$\left.\begin{aligned} W_1(j\omega) &= \frac{(T_3 j\omega_1 + 1)}{(T_1 j\omega_1 + 1)(T_2 j\omega_1 + 1)} = K_1 \cdot e^{j\alpha_1};\\ W_3(j\omega) &= \frac{(T_3 j3\omega_1 + 1)}{(T_1 j3\omega_1 + 1)(T_2 j3\omega_1 + 1)} = K_3 \cdot e^{j\alpha_3};\\ W_5(j\omega) &= \frac{(T_3 j5\omega_1 + 1)}{(T_1 j5\omega_1 + 1)(T_5 j5\omega_1 + 1)} = K_5 \cdot e^{j\alpha_5}. \end{aligned}\right\} \quad (7)$$

Such a system (7) is easily solved by modern computing means. For example, in Matlab the solution of the system of equations (7) is carried out by the command [T1, T2, T3] = *solve* (...) and as a result there are required values T_1, T_2 and T_3.

To build a mathematical model that allows verification of the results of identification of the parameters of the expression (1), use the tools Matlab/Simulink. Matlab/Simulink is a graphical simulation environment. This environment allows using flowcharts in the form of directed graphs, to build mathematical models of dynamic systems, including discrete, continuous, hybrid, nonlinear and discontinuous systems, to conduct Fourier analysis and other mathematical calculations and actions.

Verification of results of identification of parameters of (1) is feasible by mapping the results. Verification is carried out based on comparison of the results of the computer experiment «zigzag 10-10» (obtained on a full-scale DMI-model of the vessel) and the corresponding results of mathematical modelling in the environment Matlab/Simulink. The results of a computer experiment «zigzag 10-10» will be presented in the form of data tables as a function of time, approximating intermediate values (Fig. 3).

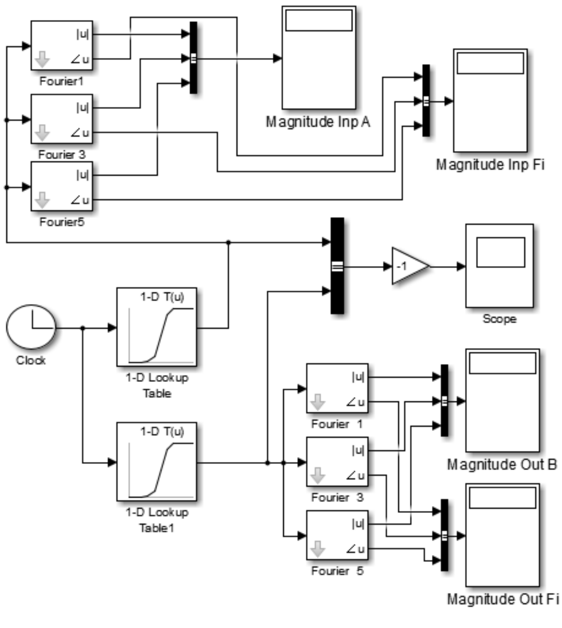

Figure 3. Fourier analysis of experimental results «zigzag»

Next, we will present (6) in the form of:

$$W(s) = \frac{\omega(s)}{\alpha_r(s)} = \frac{(T_3 s + 1)}{(T_1 s + 1)(T_2 s + 1)} = \frac{(T_3 s + 1)}{(T_1 \cdot T_2 s^2 + (T_1 + T_2)s + 1)}. \quad (8)$$

The theory of automatic control and regulation, for example, [20], allows us to present expressions like (8) in the form of block diagrams (block diagrams). Moreover, the structural scheme in the form of a Cauchy problem contains only the blocks of integration, and algebraic summation of the proportional gain.

It is obvious that with such a representation it is easy to take into account the (6). nonlinearity of H (ω), which was discarded earlier in addition, the mathematical model will take into account that:

a) the course angle is determined by the integration of the angular frequency ω;

b) steering gear α_r at the right time, according to the control algorithm «zigzag», modelled element «hysteresis loop» – «Relay block»;

c) the dynamics of the steering machine, limiting the speed of the steering, we present as a Subsystem.

Taking into account the said above, the block diagram of the mathematical model describing the «zigzag» experiment in the Matlab / Simulink environment is shown in (Fig. 4). The scheme takes into account the transition «rad/s – degrees». The (Fig. 5) shows the block diagram of the Subsystem, simulating the dynamics of the steering machine.

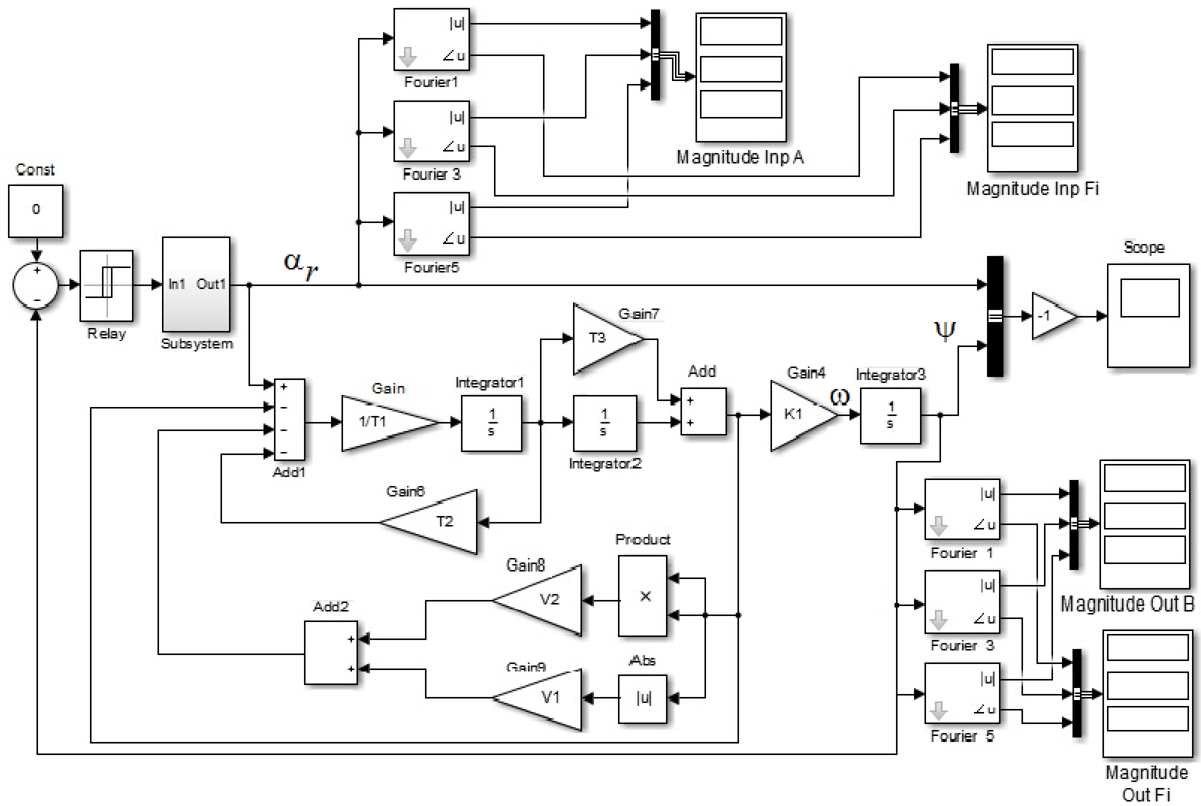

Figure 4. Block diagram, describing the experiment as «zigzag» and Fourier analysis

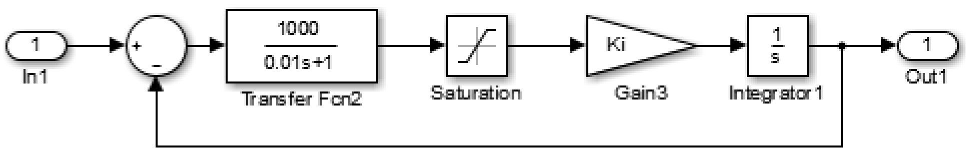

Figure 5. Subsystem: block diagram of the steering machine

The following parameters of a multi-purpose vessel of icebreaker type are taken as initial data.

1. Length of the vessel on design waterline, L_{dv} = 70,50 m.

2. Draught of ship at amidships, d_a = 3,50 m.
3. The ratio of the overall completeness, δ = 0,664.
4. The coefficient of completeness of amidships frame, β = 0,903.
5. Factor to the design load waterline, α = 0,858.
6. The wetted area of the vessel, S = 1240 m^2.
7. The area of the protruding parts, F_p = 5 m^2.
8. The speed interval of the vessel, V = 2...20 knots.
9. Volumetric displacement, W = 2864 m^3.
10. Total power SPP, N = 4600 kW.

With the help of a full-scale vessel movement simulator of the National University «Odessa Maritime Academy», for DMI-model of multi-purpose vessel icebreaker-type were conducted computer experiments and built:

a) static dependence of the steady angular frequency of circulations ω in the function of rudder angle α_r (controllability diagram;

b) manoeuvring test «zigzag 10-10».

The results of the manoeuvre test are presented in the form of appropriate tables to be inserted into the Lookup Table building blocks of the Matlab / Simulink simulation environment. The entrance table is the timer of model time Clock, outputs the rudder angle and heading angle.

Processing of the results according to the expression (3) and the subsequent solution of the excess system of equations allowed to identify the values K, ν_1, ν_2.

Simulation of the manoeuvre test «zigzag 10-10», based on the tables Lookup Table (Fig. 3) with treatment of results of Fourier analysis on (7) and the subsequent solution of this system, allowed to find the remaining members of the equation (1) – T_1, T_2 and T_3. On this basis, is constructed the model shown in (Fig. 4). The parameters of the model are given in (table 1).

Table 1. Identified parameters

K	ν_1	ν_2	T_1	T_2	T_3
0,031	$-1{,}7\cdot10^{-3}$	$-6{,}1\cdot10^{-4}$	31	15	5

The rate of increase in the change in the rotation of the steering machine was 3 degrees/s. In (Fig. 6) shows the results of verification of the experimental and identified model of the «zigzag 10-10» test. In (Fig. 6) the dotted line (index 1) shows the experimental data, solid line (index 2) – simulation data.

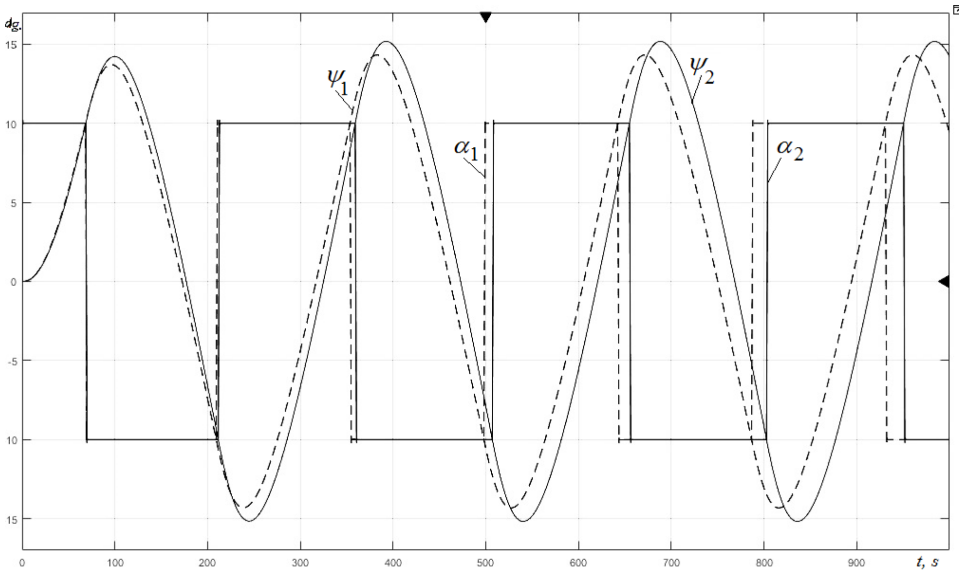

Figure 6. Verification of results of simulation of manoeuvre test «zigzag»: 1 – experiment, 2 – model

The proposed in the article calculation methodology and the set of end formulas such as (3), (4) and (7) make it possible easily to process the data on diagram of ship's steering quality as well as the zigzag maneuver. Subsequent processing consists of the following stages:

a) the method of solving an overdetermined equation system constructed on the basis of expression (3);

b) the use of the Fourier expansion of the data obtained from the maneuver tests «zigzag»;

c) the solution of equation system by standard mathematical means such as Matlab, Mathcad or others, allows us to quickly find the unknown coefficients of model (1) of ship's steering quality.

It should be noted that the use of calculation methodology requires careful maneuvering, reliable amplitude measurement, period and phase to obtain consistant results. The final result of identification of the parameters of Nomoto's equation (1) strongly depends on the quality of the actual experiments or the quality of similar experiments with ship's models (virtual or physical – in experimental basins).

It may be considered that it is sufficient to conduct one test of steady turning and one «zigzag» test, which reduces the required amount of initial data.

The proposed approach to solving the problems of identifying the parameters of the Nomoto equation is confirmed by modeling. When modeling, taking into account a very small number of parameters, this approach contributes to obtaining sufficiently accurate results. This accuracy is quite enough for practical application – in the synthesis and tuning of the regulator setting of ship's control system on course. In this regard, it should be taken into account that an area of using the considered technique has certain limitations, i.e. it can be used to study «weak» maneuvers.

In addition, it should be mentioned that parameters of the model (1) depend on the vessel's speed. The provided method of calculation methodology parameters of the mathematical model of the vessel using the results of full-scale experiment, enables to recommend it for parameters identification of mathematical models of different types of vessels. The further research is needed to carry out for the practical implementation of the methodology (controller synthesis) in the adaptive autopilot.

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References

[1] Fossen T I and Smogeli O N 2004 Nonlinear Time-Domain Strip Theory Formulation for Low-Speed Maneuvering and Station-Keeping *Modelling, Identification and Control*, *MIC* 25(4) p 201–221

[2] Fossen T I 2005 A Nonlinear Unified State-Space Model for Ship Maneuvering and Control in a Seaway *Journal of Bifurcation and Chaos* (Plenary Talk ENOC'05, Eindhoven, The Netherlands) p 355–361

[3] Perez T and Fossen T I 2007 Kinematic Models for Sea-keeping and Maneuvering of Marine Vessels *Modelling, Identification and Control*, *MIC* 28(1) p 1–12

[4] Perez T and Fossen T I 2006 Time-Domain Models of Marine Surface Vessels for Simulation and Control Design Based on Sea-keeping Computations (Plenary Talk) *Proc. of the IFAC* (MCMC'06, Lisbon, Portugal) p 20–24

[5] Budashko V V, Onishchenko O A 2014 Mathematical foundations of simulation simulation of the control system of the power installation of a drilling vessel *Bulletin of the Kamchatka State Technical University* (Petropavlovsk-Kamchatsky: Kamchatka State Technical University) Issue 29 p. 6–13

[6] Budashko V V, Onishchenko O A 2014 Improvement of the control system of the propulsion device of the combined propulsive complex *Bulletin of the National Technical University "KhPI". Collection of scientific works. Series: Electric machines and electromechanical energy conversion* (Kharkov. NTU "KhPI") 38 (1081) p. 45–51

[7] Sutulo S and Soares Guedes 2011, Mathematical Models for Simulation of Maneuvering Performance of Ships *Marine Technology and Engineering* (Taylor & Francis Group, London) p 661–698

[8] Budashko V V, Onishchenko O A, Yushkov E A Physical modeling of a multifunctional propulsion complex *Zbirnik Naukovych prac Vijskovo Akademii (m. Odesa). Technical sciences* 2 p 88–92

[9] The Maneuvering Committee 2005 *Final Report and Recommendations to the 24th ITTC* (UK) 1, p 137–198.

[10] Nomoto K, Taguchi T and Hirano S 1957 On the steering qualities of ship *International Shipbuilding Progress* 4 35 p 56–64

[11] Yongbing Chen, Yexin Song, Mianyun Chen 2010 Parameters identification for ship motion model based on particle swarm optimization *Kybernetes* 39 Issue 6 p871–880 https://doi.org/10.1108/03684921011046636

[12] Ma F C and Tong S H 2003 Real-Time Parameters Identification of Ship Dynamic Using the Extended Kalman Filter and the Second Order Filter *IEEE Conference on Control Applications* Vol. 2 p 1245–1250

IOP Conf. Series: Earth and Environmental Science **172** (2018) 012010 doi:10.1088/1755-1315/172/1/012010

[13] Casado M H, Ferreiro R and Velasco F J 2007 Identification of Nonlinear Ship Model Parameters Based on the Turning Circle Test *J. Ship Res.* 51(2) p 174–181
[14] Sheng L, Jia S, Bing L and Gao-Yun L 2008 Identification of Ship Steering Dynamics Based on ACA-SVR *IEEE International Conference on Mechatronics and Automation* p 514–519
[15] Agarkov S A, Pashentsev S V 2015 Parametric identification of the generalized Nomoto model using the apparatus of the calculus of variations *Bulletin of MSTU* Vol. 18 1 p. 7–11.
[16] Pashentsev S V 2010 Parametric identification of maneuverability characteristics based on the results of full-scale tests of the Zigzag type in the non-linear model of vessel controllability *Vestnik MSTU* Vol. 13 4/1 p 730–735
[17] Journée J M J 1970 A simple method for determining the manoeuvring indices K and T from zigzag trial data *Delft University of Technology, Ship Hydromechanics Laboratory Report 267*
[18] Stevens Scott A 2017 System Analysis – Rank and Nullity *Math 220 – Matrices Handouts* (Pennsylvania State University) 3 p 115–119
[19] Anton Howard Rorres Chris 2005 Elementary Linear Algebra (9th ed.). *John Wiley and Sons* ISBN 978-0-471-66959-3
[20] Golnaraghi F, Kuo B C 2010 *Automatic Control Systems* (Wiley) p 786.