A New Approach of Genetic Algorithms to Tuning Parameters of Backstepping Ship Course Controller

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Abstract. One of the methods which can be used for designing a nonlinear course controller for ships is the backstepping method. The parameters of the obtained nonlinear control structures were tuned to optimise the operation of the control system. The optimisation was performed using genetic algorithms. The quality of operation of the designed control algorithms was checked in simulation tests performed on the mathematical model of the tanker completed by steering gear. The goal of this paper is not to present or propose any new solusion in programming of genetic algorithm. It will be rather focused on possibility of use genetic algorithm in backstepping method.

1 Wstęp

The choice of the parameters of backstepping ship course controller with regard to compound ship models is not an easy task to do taking into consideration the nonlinear working system and the complicated control unit structure. The impediment is the change of the system dynamics depending on the working point and stem parameters time variability which was caused by the course modification, speed, loading state or the influence of the environment disturbance. The analysis of the regulation system structure taking into consideration parameters variability could lead to more precise control over the vessel movement in various system working conditions.
The control structures using the backstepping method found in modern literature were mainly optimised either on the basis of classical method or tuned by means of intuition experiment. The classical method has in its ground in solving differential and integral equations. [6, 3]. The analytical techniques are complicated mathematically, they require the knowledge of the mathematical model of the object and suggest the linear change of the parameter regulations [5]. In the following article there was introduced the automatic optimizing parameter course controller technique using the backstepping method with genetic algorithm. Such kind of technique has never been used in dealing with such kind of a problem. The control system based on the backstepping method using the evolutionary method seems to be a good alternative for other solutions in connection with nonlinear character and simplicity of the evolutionary algorithm. What is more, the genetic algorithm allows designing the control system regulations where the assumption of the parameters linearity is not required. The usage of the genetic algorithm in apply to the identification of the backstepping ship course controller parameters does not introduce the limits for the number of the tuning parameters which is convenient as the number of the tuning parameters of the stabilizing functions depends on the number of the

variables present in a model and the variable of the high rank could be really high. The work of the genetic algorithm was based on the denouement generating through the imitation of the evolutionary process [4, 7] The quality of operation of the designed control algorithms was checked in simulation tests performed on the mathematical model of the tanker. In order to obtain the reference results, to be used for comparison with those recorded for the nonlinear controllers designed using the backstepping method, a control system with the PD controller was examined as well.

2 The mathematical model of ship tanker

The objective in the tanker ship control problem is to control the ship heading, $\psi(t)$ by moving the rudder δ(t), independently of the changing ship loading state. The tanker ship is described by Astrom and Wittenmark in „Adaptive Control" [1, 2] and modelled by a third-order nonlinear differential equation (1), that is used in all simulations and given by

$$\dddot{\psi}(t)+\left(\frac{1}{T_1}+\frac{1}{T_2}\right)\ddot{\psi}(t)+\frac{1}{T_1T_2}H(\dot{\psi}(t))=\frac{K}{T_1T_2}(T_3\dot{\delta}(t)+\delta(t)), \tag{1}$$

where nonlinear function $H(\dot{\psi}(t))$ expresses the steady-state relation between $\delta(t)$ and $\dot{\psi}(t)$, when $\dddot{\psi}(t)=\ddot{\psi}(t)=\dot{\delta}(t)=0$ and in the present article is approximated by the following function

$$H(\dot{\psi}(t))=\alpha\dot{\psi}^3(t)+\beta\dot{\psi}(t) \tag{2}$$

The constants α and β are assigned a value of one for all simulations. Parameters K, T_1, T_2, T_3 are defined as

$$K=K_0\left(\frac{u}{L}\right),\ T_i=T_{i0}\left(\frac{L}{u}\right),\quad i=1,2,3, \tag{3}$$

where u is the longitudinal speed of the ship in [m/s], and L is ship length in [m]. For the tanker ship L = 350 [m] , u = 5 [m/s]. In the article, the tanker is examined in two loading states. In the first state, bearing the name of the ballasting state, the ship is without cargo (liquid) and in this case the model parameters take the values K_0 =.5.88,, T_{10} = 16.91, T_{20}= 0.45, T_{30} = 1.43. The second state of tanker's operation refers to the tanks fully loaded with the transported liquid and bears the name of the full load state. In this case the model parameters take the values K_0 = 0.83, T_{10}=2.88, T_{20}= 0.38, T_{30}, = 1.07.

The rudder angle δ(t) is computed by the steering gear dynamic equation (4) described by [9]

$$\dot{\delta}(t)=\frac{K_R}{T_R}\delta_z(t)-\frac{1}{T_R}\delta(t), \tag{4}$$

where parameters T_R =156 [s], K_R =96 [deg].

3 Designing nonlinear controller

The control rule was derived for the full nonlinear mathematical model given by equation (1) with the steering gear dynamical (4). The third-order yaw dynamics model can be written in SISO strict feedback form as

$$\begin{aligned}
&\dot{x}_1(t) = x_2(t),\\
&\dot{x}_2(t) = x_3(t),\\
&\dot{x}_3(t) = -\frac{1}{T_1T_2}H\big(x_2(t)\big) - \left(\frac{1}{T_1} + \frac{1}{T_2}\right)x_3(t) + x_4(t),\\
&\dot{x}_4(t) = -\frac{1}{T_R}x_4(t) + \frac{K_R}{T_R}u(t),
\end{aligned} \tag{5}$$

where $x_4(t)=\delta_z(t)$ is the set rudder angle and $u(t)$ is the controlling input given by the backstepping control law. In backstepping method [3] arduous and time-consuming calculations were introduced therefore in this article was limited to performance of the most important and typical for this method equations only. In shortcut, when designing steering rules with the aid of the backstepping method, new state variables z_i and stabilising functions α_i are introduced, in a recurrence way, at i-th step. In the examined system following new state variables are introduced: z_1 which represents the minimised course error, z_2 which is the stabilised angular speed of the ship $\dot{\psi}(t)$, z_3 which refers to the acceleration, and z_4 which refers to the rudder angle.

$$\begin{aligned}
z_1 &= e_\psi(t) = x_1(t) - \psi_z(t),\\
z_2 &= x_2(t) - \alpha_1(z_1),\\
z_3 &= x_3(t) - \alpha_2(z_1,z_2),\\
z_4 &= x_4(t) - \alpha_3(z_1,z_2,z_3),
\end{aligned} \tag{6}$$

where $\psi_z(t)$ is the set ship course, and $\alpha_1(z_1)$, $\alpha_2(z_1,z_2)$, $\alpha_3(z_1,z_2,z_3)$ are the stabilising functions constructed in every consecutive step.

$$\begin{aligned}
&\alpha_1(z_1) = -k_1z_1 + \dot{\psi}_z(t),\\
&\alpha_2(z_1,z_2) = -k_2z_2 - z_1 + \dot{\alpha}_1(z_1),\\
&\alpha_3(z_1,z_2,z_3) = \frac{1}{T_1T_2}H(x_2(t)) + \left(\frac{1}{T_1} + \frac{1}{T_2}\right)x_3(t) + \dot{\alpha}_2(z_1,z_2) - k_3z_3 - z_2.
\end{aligned} \tag{7}$$

The stable rule of control is obtained for $u(t)$ in the system of new variables

$$u(t) = \frac{T_R}{K_R}\left(\frac{1}{T_R}x_4(t) + \dot{\alpha}_3(z_1,z_2,z_3) - k_4z_4 - z_3\right). \tag{8}$$

The parameters k_1, k_2 , k_3, k_4>0 in control rule were tuned by using genetic algorithm described in Chapter 4.

4 Tuning parameters of nonlinear controller

The process of optimising parameters for the derived control rule of the nonlinear controller given by the formula (8) was performed using genetic algorithm, which recently have gained the status of one of most popular optimisation methods [4, 7]. Below was described particular steps of operation of a used genetic algorithm.

Creating the initial population. In order to initiate the initial population the chromosomes are generated randomly using the bit-by-bit method. The length of the chromosome depends on the number of parameters to be coded, their maximum and minimum values k_{max}, k_{min} and their accuracy n, according to the formula

$$(k_{\max} - k_{\min}) \cdot 10^{n_i} \leq 2^{m_i} - 1 \tag{9}$$

where: n – number of meaningful decimal places defining the accuracy of the parameter, mi – length of the code sequence for the coded parameter.

Decoding. From the chromosome extracted are the successive sequences of bits that correspond to the coded parameters. The decimal value for each parameter is calculated using the following formula where: decimal(1010...0112) is equal to the decimal value of the binary chain.

$$k = k_{\min} + decimal(1010...011_2)\frac{(k_{\max} - k_{\min})}{2^{m_i} - 1} \tag{10}$$

Simulations and evaluation cost. The quality of control of the ship course controller was evaluated here with the aid of a digitised version of the integral quality coefficient, having the form:

$$J_E = \frac{1}{N}\sum_{i=1}^{N}(\Delta\psi_i(t))^2 + \lambda\frac{1}{N}\sum_{i=1}^{N}\delta_i^2(t) \tag{11}$$

where N is an integer number of iterations in control simulations, λ is the scale factor, in the examined case $\lambda = 0.1$, $\Delta\psi_i(t)$ is the i-th course error determined by subtracting the obtained course from its set value, $\delta_i(t)$ is the i-th angle of the rudder deflection. The genetic algorithm minimises the value of the function (11), by minimising both the course error $\Delta\psi$ and the rudder angle $\delta(t)$. The component connected with the rudder angle is scaled to have a similar amplitude to that of the course error.

Genetic operations. Genetic operations comprise selection, crossover, and mutation. More information about used genetic operation can find in the previous paper [8].

The tuning programme works until conditions for its stop are met. Two types of algorithm stop conditions are possible. The first condition consists in limiting the maximum number of generations in the optimisation process, while in the second condition the algorithm checks whether the newly generated populations improve considerably the previously obtained solutions. The entire process is repeated until the maximum number of generations is reached. The final solution was the best solution in the most recent population.

5 Simulation tests

In order to evaluate the quality of the algorithm of nonlinear control, simulation tests were performed using the programme package Matlab/Simulink. The simulation tests were performed in the configuration shown in Figure 1. In the window „Ship" the equations of the ship dynamics characteristics, given by formula (1), were modelled. The model was complemented by the dynamics of the steering gear (4). In the window „Course controller" the examined ship course controller, given by formula (8) was placed.

Tuning the course controller parameters with the aid of the genetic algorithm made use of the ship dynamic characteristic equations, with the parameters set for the ballasting state. The set course was rapidly changed by 40 [deg]. The quality coefficient, given by formula (11), was determined from the test trials performed within 500 [s] with sampling period 0.01 [s].

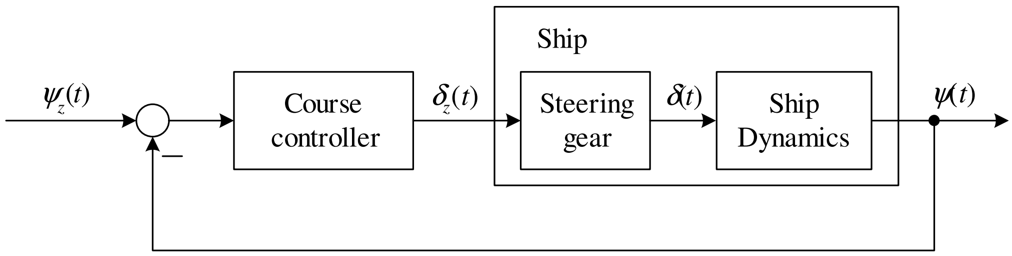

Figure 1. Block diagram of the examined control system

The parameters of the genetic algorithm were: the probability of crossover was $p_c = 0.60$, while the probability of mutation was $p_m = 0.01$. The population consisted of 50 chromosomes. 10 tests of tuning the controller parameters with the aid of the genetic algorithm were performed, and their results are collected in Table 1. The maximum number of generations for each test was equal to 100. The best values of the tuned parameters for the examined nonlinear controller were k_1=54.79, k_2=115.8, k_3=0.0078, k_4=0.7716. These are the parameter values at which the minimum values of the quality coefficient were obtained at the stage of tuning with the aid of the genetic algorithm. The minimum level of quality coefficient was obtained in sample 6. The example process of tuning parameters for the nonlinear controller with four parameters is shown in Figure 2.

Table 1. Results of tuning the settings for nonlinear controlled (8) with the aid of genetic algorithm.

Test no.	N	k_1	k_2	k_3	k_4	J_E
1	10	118.98	535.2	0.1260	0.2598	234.5242
2	26	145.59	812.0	0.0944	0.5512	234.6294
3	71	125.24	605.9	0.0079	0.5118	234.5425
4	48	56.75	121.5	0.1653	0.4252	234.0173
5	26	145.59	812.0	0.0945	0.5512	234.629
6	52	54.79	115.8	0.0078	0.7716	233.9628
7	13	90.02	311.9	0.0315	0.9685	234.3603
8	58	131.89	677.4	0.0157	0.8976	234.5729
9	32	131.50	629.5	0.2677	0.2441	234.5972
10	31	197.26	717.507	1.0394	0.48819	234.9652

6 Comparison result with PD linear controller

The investigations consisted in comparing the results of the tuned nonlinear controllers having four parameters with the conventional PD controller. To compare results PD controler was tuned by the same genetic algorithm in the same the algorithm working conditions Figure 3a presents the results of the simulation tests performed with two controllers: the conventional linear PD controller the results of which are marked with dashed line, and the nonlinear controller with four parameters (8), marked with continuous line. All controllers were tuned for the ship dynamic characteristic equations corresponding to the ballasting state, but in this part of analysis in the first 1000 [s] of the tests, the mathematical model of the ship made use of the parameters corresponding to the ballasting state, while during the remaining time the full load parameters were applied. For the sytuation shown in a Figure 3a the exact values of the time quality coefficients, determined from the step response of two controllers for two load states, are collected in Table 2, where the used symbols are the following: t_n– the rise time, calculated as the time interval during which the output signal has changed from 10% to 90% of the set value, yust, Mp – maximum over-regulation, expressed in percents and calculated as Mp = 100%(ymax - yust)/ yust, t_R – the time of control, calculated as the time interval from zero to the instant at which the controlled (output) signal reaches steadily the 1% accuracy zone of the set value,
J_C– the quality integral coefficient described by equation (11).

Table 2. Estimated values of time quality coefficients:

	Ballasting state				Full load state			
	t_n	M_p	t_R	J_c	t_n	M_p	t_R	J_c
	[s]	[%]	[s]	[-]	[s]	[%]	[s]	[-]
PD	170.68	0.81	308.15	268.6663	148.34	3.29	508.38	156.2852
Backstepping	131.71	0.18	261.77	233.9747	115.09	18.00	439.77	154.307

Figure 3b presents an example ship trajectory with the beginning at point (0,0) and the initial ship course ψ_0=0 [deg]. The tanker model is led along the course defined by the following turn points. The defined heading angle is determinated trigonometrically on the base of straight line between the present tanker location and the position at the turning point. The successive turning points are marked in the table by circuits. The figure compare two trajectories for systems: with PD course controller (dashed line) and course controller designed by backstepping method (solid line). In this case the tanker has the parameter set for ballasting state.

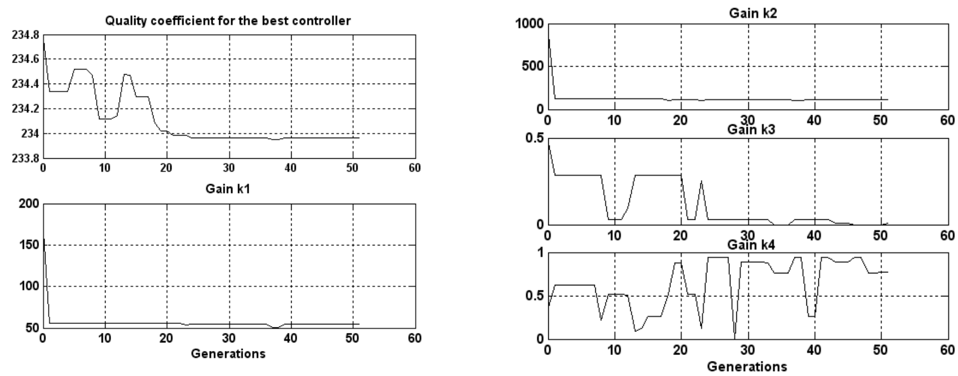

Figure 2. The process of tuning parameters for the nonlinear controller with four parameters.: quality coefficient for the best controller and parameters k_1, k_2, k_3, k_4

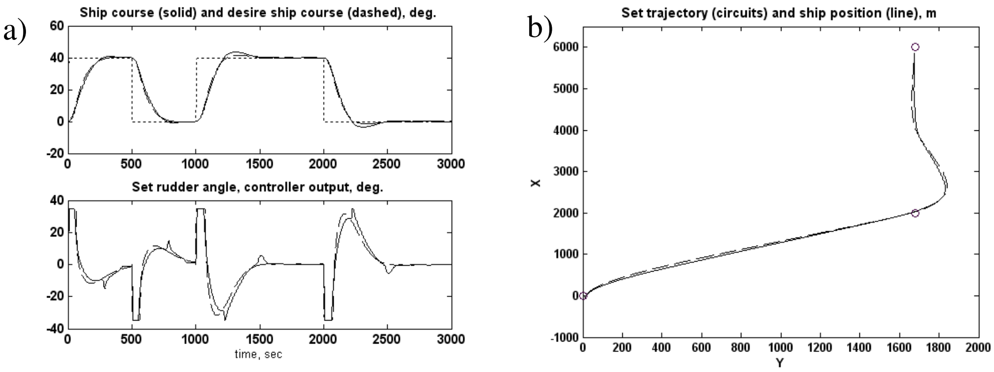

Figure 3. Comparing results of simulation with tuned controllers: PD (dashed line), nonlinear controller with four parameters (solid line). (a) ship course and rudder angle (b) ship position (x, y) along the set trajectory (circuits)

7 Conclusion

The article discusses method which can be used to tuning the parameters of nonlinear control rule designed with the aid of the backstepping method and used for controlling the ship motion on the course. Nonlinear controllers designed with the aid of the backstepping method require tuning of their parameters to the optimal values. The use of genetic algorithms for this purpose produced excellent results. Sample results illustrating the process of tuning the parameters for the nonlinear controller were shown in Figure 2. The parameters were tuned in the control system taking into account the presence of the steering gear and the dynamic characteristics of the ship corresponding to the ballasting state.

Moreover, in order to obtain the reference data for comparison, a conventional PD controller was examined, which was also tuned with the aid of genetic algorithms for the same conditions as in the case of the nonlinear controllers.

The quality of operation of the examined controllers was evaluated from the tests checking the effect of ship parameter changes. Two states of ship load were analysed, which were the ballasting and the full load. Step responses were examined to the set ship course change by 40 [deg]. As shown in Table 2, the tests have revealed that the obtained results are comparable for controllers when the ship was in the ballasting state, slightly better results were obtained for the backstepping method. When the ship was in the full load state better results were produced by the PD controller than by the nonlinear controller designed using the backstepping method. The reason of this regularity lies in the fact that the parameters of the controllers were only tuned for the ballasting state and then were used unaltered for the full load state, which was the source of some error. It turned out that the backstepping method is more sensitive to changes of parameters than the PD controller, which seems to be more robust. The backstepping method requires precise information on the model of the examined object and its varying parameters, which is extremely difficult in practical applications. Therefore it is necessary to perform the analysis of the model parameters using adaptation techniques, which will be examined in the nearest future.

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