

Ship course control system taking into account the steering gear dynamic properties

Sterownie kursem statku z uwzględnieniem własności dynamicznych maszyny sterowej

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Key words: autopilot, nonlinear control, backstepping method, genetic algorithm

Abstract

The article presents various configurations of nonlinear ship course controllers. The controllers were designed based on backstepping method, the PD and sliding mode control. The controller versions at the design stage take into account the dynamic properties of the steering gear. A simplified simulation model of the B-481 type vessel, including wave and wind effects, was applied to simulate the control algorithm by using time domain analysis. The results of computer simulations have shown the advantages of control algorithms taking into account the dynamics of steering gear such as the increasing the economic efficiency of system operation, the reducing rudder activity and increasing the average speed of the vessel during the voyage.

Słowa kluczowe: autopilot, nieliniowe sterowanie, metoda backstepping, algorytm genetyczny

Abstrakt

W artykule zostały przedstawione różne konfiguracje regulatorów nieliniowych do sterowania kursem statku. Dwie z nich uwzględniają na etapie projektowania liniowe własności dynamiczne urządzenia wykonawczo-sterującego maszyny sterowej. Projekty regulatorów oparto na metodzie backstepping, regulatorze PD oraz sterowaniu ślizgowym. Dokonano analizy porównawczej jakości pracy rozpatrywanych struktur sterowania podczas badań symulacyjnych na pełnowymiarowym modelu symulacyjnym statku typu B-481. Wyniki badań symulacji komputerowych wykazały przewagę algorytmów sterowania z uwzględnieniem dynamiki maszyny sterowej poprzez zwiększenie wydajności ekonomicznej pracy układu, zmniejszenie aktywności steru oraz zwiększenie średniej prędkości statku podczas podróży.

Introduction

Numerous investigations which were oriented on the design of an integrated ship control systems have been performed recently. Despite significant improvement in automation, the course control is still an active field of research. The control algorithms presented in the literature for course changing, course – keeping process are mainly based on simplified dynamic ship models. This include the linear – quadratic techniques, H1 control [1, 2], feedback linearization control, disturbance rejection control [3, 4, 5], sliding mode control [6, 7] and backstepping control [8]. These methods give solu-

tions which are not fully satisfying. Nowadays, the autopilots which are installed on the ships usually use the algorithms of the PID controller, because of the simplicity, the reliability and the easiness of construction. Although some progress was made in that method, (fuzzy PD, ADRC, PD-backstepping) some disadvantages are still exposed. This is due, among the other things, to the fact that high precision model is required in H1 control, generalized forecast control, feedback linearization and backstepping method.

Occurring uncertainties are frequently encountered difficulties while describing the simplified ship course model. They might be a result of meas-

uring errors, numerical errors of model, unknown nonlinear functions, unknown parameters or structural errors. More accurate structure of a model indicates higher chances of gaining better quality control. Taking into account the dynamics of operative devices like a steering gear is important when choosing appropriate structure of simplified model of on-course steering device. Neglecting the dynamics of the steering gear is equivalent to decrease in accuracy of assumed model on which based the designing of the control law. In marine technology there is an essential problem in regard to the steering gear dynamics at the design stage. This is due to its nonlinear dynamics, which is described using the nonlinearity with saturation. The steering gear dynamics is usually not taken into consideration by the control algorithms available in the literature.

The article presents two different configurations of nonlinear controllers for steering the course of a ship, using the backstepping method. Versions A and B require a precise knowledge about the dynamics model of the ship. Moreover, controller - version B takes into account the dynamic properties of operative device of steering gear at the design stage. Setting parameters of resulting nonlinear control structures were adjusted in order to optimize the system performance. The optimization included genetic algorithms. Quality of performance of resulting control structures was analyzed through the simulation research of simplified model of the B-481 type ship. Research has proven that taking into account dynamic properties of steering gear at the design stage reduces the rudder activity during the stabilization of a ship on appointed course. Therefore, the steering gear does less movement, which in turn reduces its operation, and manoeuvring requires lower angular velocity. It also entails smaller speed loss of the ship during the manoeuvres. Operation quality of the backstepping controller in a ship course control system was compared with the ones of PD and the SMC (Sliding Mode Control) controllers.

Mathematical ship's model

In ship motion control systems the course stabilization task is usually realized by using the linear models which describe a linear relation between the rudder deflection angle and the ship course. This linear relation becomes insufficient for controlling the ship during course change manoeuvres. The instantaneous velocity of the ship decreases during such manoeuvres. It is a result of the increasing resistance to motion which appears when the ship turns. Taking this effect into account, the synthesis of the ship course control laws will be done using

the nonlinear mathematical model proposed by Van Leeuwen [9]. This model, described by the differential equation (1), presents the nonlinear changes of ship's angular velocity r depending on instantaneous changes of ship's velocity U and the rudder deflection angle δ .

$$T_1^* T_2^* \left(\frac{L}{U}\right)^2 \ddot{r} + (T_1^* + T_2^*) \frac{L}{U} \dot{r} + \frac{U}{L} H_N \left(\frac{L}{U} r\right) = \frac{U}{L_S} K^* \delta \quad (1)$$

where:

$$H_N \left(\frac{L}{U} r\right) = a_0^* + a_1^* \frac{L}{U} r + a_2^* \left(\frac{L}{U}\right)^2 r^2 + a_3^* \left(\frac{L}{U}\right)^3 r^3 \quad (2)$$

- H_N – nonlinear manoeuvring characteristic of the ship;
- a_i^* – manoeuvring characteristic coefficients,
- L – ship length, in [m];
- U – instantaneous ship velocity, in [m/s];
- T_1^*, T_2^*, T_3^* – dimensionless time constants;
- K^* – dimensionless amplification.

The time constants and amplifications were determined from the results of the manoeuvring tests which are simulated on the full-scale mathematical model of B-481 container ship with length about $L = 181$ m. The model allows analyzing the behavior of the ship for two load conditions: ballast and full load. The manoeuvring characteristic coefficients $a_i^*, i \in \{0,1,2,3\}$ were determined in the test called the "spiral test". All parameters are given in table 1. They were determined for propeller revolution equal 1.006 rps and the set rudder angle $\delta_z = 10$ deg. Figure 1 shows the comparison of ship position and course characteristics in test turning manoeuvre by $\delta_z = 10$ deg.

Table 1. The parameters of the simplified model of B-481 ship's type

Tabela 1. Parametry uproszczonego modelu statku typu B-481

Ballast	$K_u^* [-]$	$T_u^* [-]$	$K^* [-]$	$T_1^* [-]$	$T_2^* [-]$
	0.00480	5.0	1.5	2.5	0.02
	a_3^*	a_2^*	a_1^*	a_0^*	
	0.0016	-0.0033	1.0000	-3.1667	
Full load	$K_u^* [-]$	$T_u^* [-]$	$K^* [-]$	$T_1^* [-]$	$T_2^* [-]$
	0.00470	8.0	2.2	4.7	0.05
	a_3^*	a_2^*	a_1^*	a_0^*	
	0.0033	-0.0021	1.0000	-6.6027	

The simplified model will be then used in the designing ship course control system by using the backstepping, PD and sliding method.

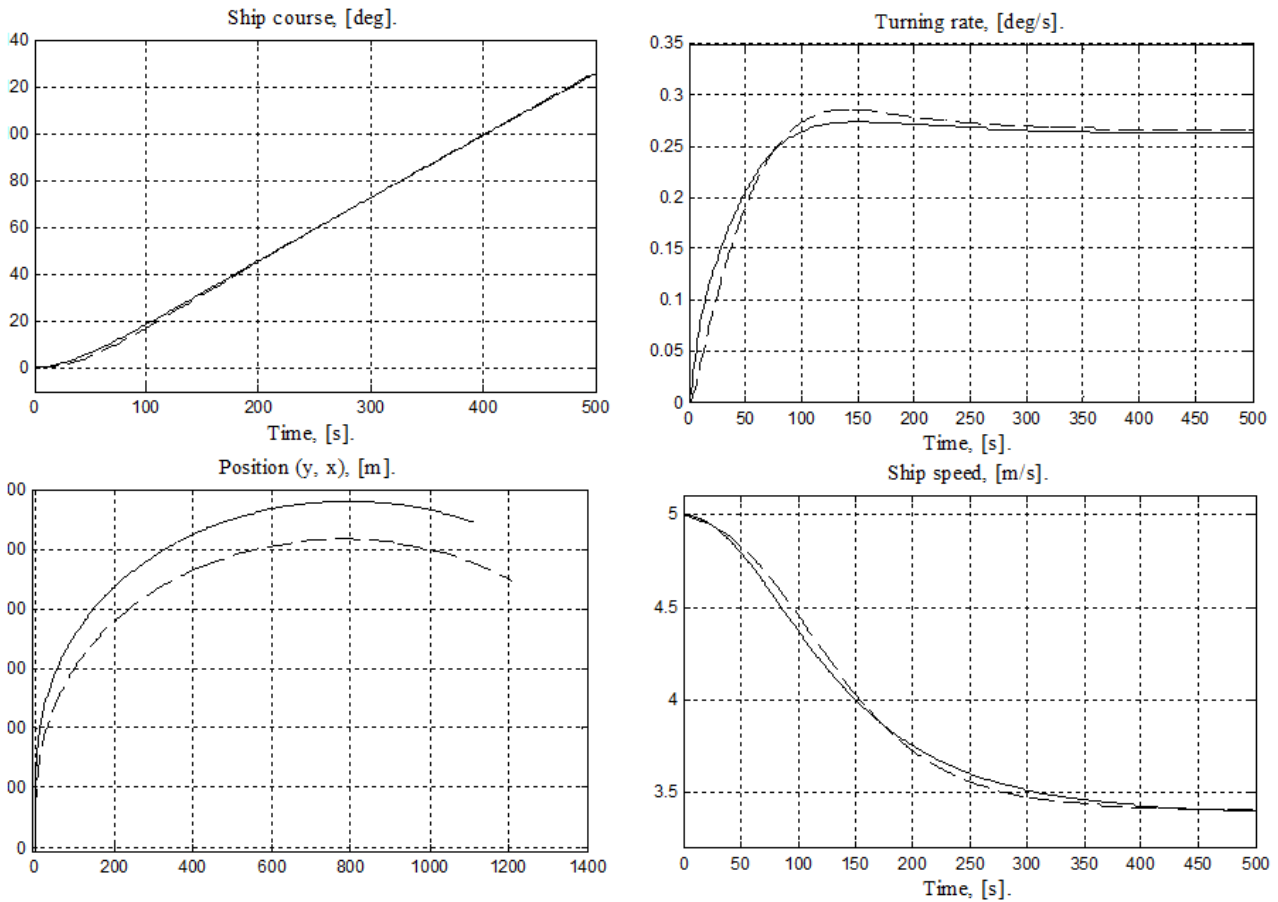


Fig. 1. Ship characteristics in test turning manoeuvre by $\delta_z = 10$ deg for ballast: solid line – full scale model, dashed line – simplified model

Rys. 1. Charakterystyki czasowe statku zarejestrowane podczas próby cyrkulacji o $\delta_z = 10$ deg dla stanu zabalastowania: linia ciągła – model pełnowymiarowy, linia przerywana – model uproszczony statku

The model of dynamic characteristics of the ship was completed by the model of the steering gear and schematically shown in figure 2.

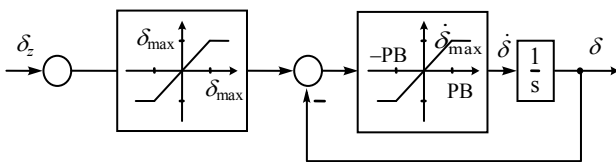


Fig. 2. Block diagram of the steering gear
Rys. 2. Schemat blokowy maszyny sterowej

In the present article assumed that the rudder is rate limited to approximately $\dot{\delta}_{max} = 2.5$ [deg/s] until $|\delta_z - \delta| \leq 3$ [deg] when the rudder operates in the linear characteristic region. The maximum rudder angle equal to $\delta_{max} = 20$ [deg]. For this assumption, the steering gear dynamical characteristic can be described by the following equation:

$$\dot{\delta}(t) = \delta_z(t) - \delta(t) \quad (3)$$

A large number of practically used control methods bases on the assumption neglecting the steering gear dynamics. In the present article, at the

stage of designing the control law the mathematical model of the ship (1) has been extended by including the simplified and linear equation of steering gear dynamics (3).

Assuming that the state variable vector is:

$$x(t) = [x_1(t), x_2(t), x_3(t), x_4(t)]^T = [\psi_z(t), r(t), \dot{r}(t), \delta(t)]^T$$

the output signal is $y(t) = x_1(t)$, set variable vector $x_z(t) = [\psi_z(t), \dot{\psi}_z(t), \ddot{\psi}_z(t), \dddot{\psi}_z(t)]^T$ and the control variable is $\delta_z = u_c(t)$, it can define the model of the examined ship with the steering gear by the set of fourth-order differential equations:

$$\dot{x}_1(t) = x_2(t) \quad (4)$$

$$\dot{x}_2(t) = x_3(t) \quad (5)$$

$$\dot{x}_3(t) = \left(\frac{U}{L}\right)^3 cx_4(t) + \varphi^T(t)\theta \quad (6)$$

$$\dot{x}_4(t) = u_c(t) - x_4(t) \quad (7)$$

in which for simplifying purposes, the following substitutions were made:

$$a = -\frac{T_1^* + T_2^*}{T_1^* T_2^*}, b_0 = -\frac{a_0^*}{T_1^* T_2^*}, b_1 = -\frac{a_1^*}{T_1^* T_2^*},$$

$$b_2 = -\frac{a_2^*}{T_1^* T_2^*}, b_3 = -\frac{a_3^*}{T_1^* T_2^*}, c = \frac{K^*}{T_1^* T_2^*}$$

$$\theta^T = [b_0, b_1, b_2, b_3, a] \quad (9)$$

$$\varphi^T(t) = \left[\left(\frac{U}{L}\right)^3, \left(\frac{U}{L}\right)^2, \left(\frac{U}{L}\right), x_2(t), x_2^2(t), x_2^3(t), \left(\frac{U}{L}\right), x_3(t) \right]$$

The system defines the constant ship model parameters b_0, b_1, b_2, b_3, a ; the vector of the ship's model parameters $\theta \in R^5$ and the state vector, related to the vector of parameters θ . All model nonlinearities are included in function φ .

Ship's course control

The ship's course control design process aims at determining the control law with the feedback. It is used for asymptotic tracking the set ship course $x_1(t)$ within the limits of the given tracking error $z_1(t) = x_1(t) - \psi_z(t)$.

PD control

Nowadays, autopilots being part of equipment on vessels use the algorithm of PD controller to adjust the course angle of a ship. The operation of a classic, conventional PD controller is defined by the following formula:

$$\delta_z(t) = K_P(\psi_z(t) - x_1(t)) - K_D x_2(t) \quad (11)$$

where K_P, K_D – are coefficients illustrating the influence of individual components of a proportional and a differentiation.

Sliding mode control

The idea of sliding mode control consists in change of the structure of the controller depending on change of the value of state error vector $\tilde{x}(t) = x(t) - x_z(t)$. The main characteristic of this type of steering is provoking a sliding motion of state trajectory on a defined sliding surface s of switchover, which is an error function. The rule of designing a conventional sliding mode controller [10] was applied to a fourth-order model (4)–(7), thereby taking dynamic properties of steering gear into account. Following formula expresses the sliding surface used for steering:

$$s(\tilde{x}) = h^T \tilde{x}(t) = h_1(\psi(t) - \psi_z(t)) + h_2(\dot{\psi}(t) - \dot{\psi}_z(t)) + h_3(\ddot{\psi}(t) - \ddot{\psi}_z(t)) + h_4(\dddot{\psi}(t) - \dddot{\psi}_z(t)) \quad (12)$$

where $h = [h_1, h_2, h_3, h_4]^T$ is a parameter vector.

A sliding mode control method that is illustrated in a basic form enables determining the control law represented by the sum of two addends:

$$u_\delta(t) = u_{eq}(t) + u_{sw}(t) \quad (13)$$

where: $u_{eq}(t)$ – a nominal part, usually designed for the linearized object, $u_{sw}(t)$ – the switching term, related to the sliding surface $s(\tilde{x})$.

The nominal part was chosen according to the formula:

$$u_{eq}(t) = -N\psi_z(t) + k^T x(t) \quad (14)$$

with a feedback vector $k = [k_1, k_2, k_3, k_4]^T$ and a gain N correcting input signal.

The switching term assumes the form:

$$u_{sw}(t) = \eta \cdot \text{sat}\left(\frac{s}{\phi}\right) \quad (15)$$

$$\text{sat}\left(\frac{s}{\phi}\right) = \begin{cases} \text{sgn}\left(\frac{s}{\phi}\right), & \text{when } \left|\frac{s}{\phi}\right| > 1 \\ \frac{s}{\phi}, & \text{when } \left|\frac{s}{\phi}\right| \leq 1 \end{cases} \quad (16)$$

Parameter η is the switching gain which determines the amplitude of the additional switching control signal, whereas ϕ is interpreted as the width of the boundary layer.

Finally, the output signal of sliding mode controller varied for a defined trajectory of control s according to the following control law:

$$u_c(t) = -N\psi_z(t) + k^T x(t) + \eta \cdot \text{sat}\left(\frac{s}{\phi}\right) \quad (17)$$

In control law, defined as u_δ , the switching gain η and the width of the boundary layer ϕ need to be tuned.

Backstepping control

When designing the control law with backstepping method, it has to assumed that it has precise information about an object, i.e. it considered the vector of parameters θ and the parameter c as known in the ship model. Then the ship course control law could be derived using the classical backstepping method, as it was discussed in detail

[11]. In the present article, the classical backstepping method was used for developing two algorithms of nonlinear ship control on the course, denoted as version A and version B. When developing the rule A of the nonlinear control, the steering gear dynamics was neglected. When developing the nonlinear control rule B, mathematical ship model with steering gear dynamic model described by equation (4)–(7) was taken into account. With the reference to previous works the resulting control laws are given in table 2.

The new state variable z_1 represents the minimized ship course error. Variable z_2 is the stabilized angular velocity and z_3 is related to the acceleration

of the ship. The role of the functions $\alpha_1, \alpha_2, \alpha_3$ is to respectively stabilize the subsystems. The fourth state variable z_4 represents the deviation of the rudder deflection angle from its set value.

Control system structure

In order to evaluate the quality of the derived algorithms of nonlinear control, simulation tests were performed using Matlab / Simulink programme package. The simulation tests were performed in the configuration shown in figure 3.

The classical genetic algorithm was applied in order to tune backstepping, PD, and sliding mode

Table 2. Resulting backstepping control law for version A and B
Tabela 2. Prawo sterowania dla wersji A i B regulatora backstepping

Version A	Version B
Error variable:	Error variable:
$z_1(t) = x_1(t) - \psi_z(t)$ (18)	$z_1(t) = x_1(t) - \psi_z(t)$ (21)
$z_2(t) = x_2(t) - \dot{\psi}_z(t) - \alpha_1(t)$ (19)	$z_2(t) = x_2(t) - \dot{\psi}_z(t) - \alpha_1(t)$ (22)
$z_3(t) = x_3(t) - \ddot{\psi}_z(t) - \alpha_2(t)$ (20)	$z_3(t) = x_3(t) - \ddot{\psi}_z(t) - \alpha_2(t)$ (23)
	$z_4(t) = x_4(t) - \left(\frac{L}{U}\right)^3 \frac{1}{c} \ddot{\psi}_z(t) - \alpha_3(t)$ (24)
Control law:	Control law:
$x_4(t) = \left(\frac{L}{U}\right)^3 \frac{1}{c} (-k_3 z_3(t) - z_2(t) - \varphi^T(t)\theta + d_2(t) + \ddot{\psi}_z(t))$ (25)	$u_c = \frac{T_R}{K_R} \left(-k_4 z_4(t) + \frac{1}{T_R} x_4(t) - \left(\frac{U}{L}\right)^3 c z_3(t) + d_3(t) + \left(\frac{L}{U}\right)^3 \rho \psi_z^{(4)}(t) \right)$ (26)
Stabilizing function:	
$\alpha_1(t) = -k_1 z_1(t)$ (27)	$\alpha_3(t) = \left(\frac{L}{U}\right)^3 \frac{1}{c} (-k_3 z_3(t) - z_2(t) + \dot{\alpha}_2(t) - \varphi^T(t)\theta)$ (29)
$\alpha_2(t) = -k_2 z_2(t) - z_1(t) + \dot{\alpha}_1(t)$ (28)	where: $k_1, k_2, k_3 > 0$ are design parameters.

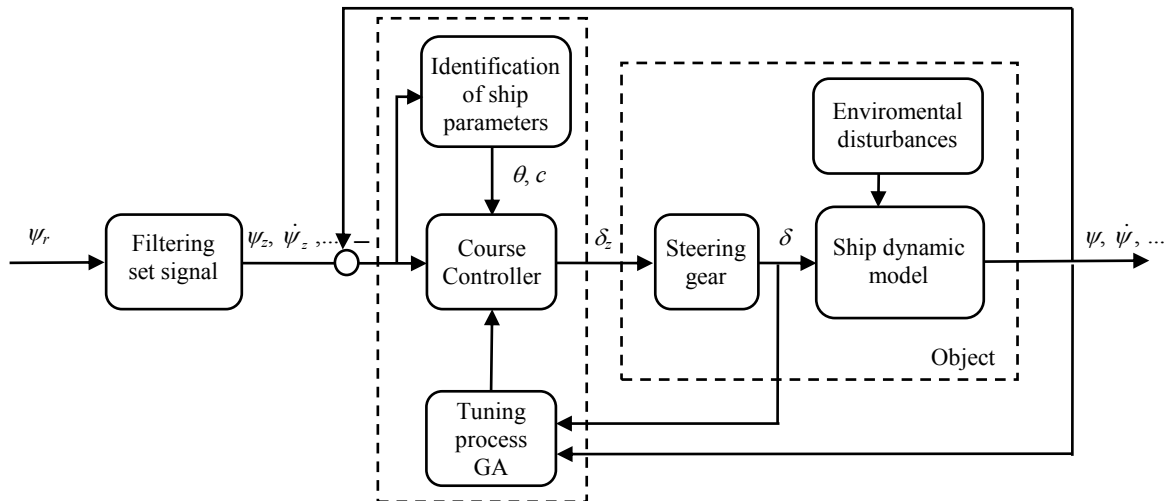


Fig. 3. General scheme of the ship's course control system
Rys. 3. Schemat ogólny układu sterowania kursem statku

controllers' parameters by offline method. Genetic operations comprised classical selection, crossover and mutation. In the genetic method all individuals (here sets of parameters) are evaluated by the cost function, which should reflect optimization criteria. The basic criterion is the economic one (30). The autopilots aim to ensure such control of the way, which enables the least deviation from the set-point by decreasing the activity of the rudder. This manner of control prevents excessive loss of speed, reduces travel time and reduces fuel consumption.

$$ISE : \min J_{c1} = \frac{0.0076}{T} \int_0^T (\Delta\psi^2 + \lambda\delta^2) d\tau \quad (30)$$

where:

- λ – the scale factor, $\lambda = 0.1$;
- $\Delta\psi$ – the course error;
- δ – the rudder deflection angle;
- J_{c1} – the loss of speed in percent.

Quality coefficient J_{c1} defines a compromise between too high steering accuracy and reduction in the use of a steering gear.

Simulation tests

Influence of steering gear on the quality of system performance

The following subsection contains the analysis of the influence of taking into account the dynamics of steering gear during the synthesis of control law on the quality of system performance. With this end in view, a comparison between the operation of a ship's course control system and versions A and B of control algorithm. The manoeuvre attempt con-

sisted of step changes in the set heading of a ship by 10 degrees to the starboard and to the port side respectively. Also, two different ship's loading states were taken into account. Mathematical model of the ship included the parameters for a ballasting state during first 2000 s of the study, and then for full load state throughout the remaining time. The settings of the course controllers were adjusted in the process of optimization with the use of genetic algorithm. Table 3 below presents the results for both controllers.

Table 3. Results of tuning settings for nonlinear controllers (25) and (26)

Table 3. Parametry nastawne nieliniowych regulatorów (25) i (26)

	k_1	k_2	k_3	k_4	ISE
Ballast					
Version A	0.020568	176.3781	2.545	–	0.0267
Version B	5.93	184.252	0.001	0.001	0.0209
Full load					
Version A	1.8795	42.5205	0.001	–	0.04671
Version B	0.001	111.8115	1.3708	0.001	0.036982

Figure 4 contains the step responses of the ship's course control system, which were recorded during the manoeuvre attempt. The exact time values of the quality coefficients, determined from the step response of all three controllers for both loading states, are collected in table 4 where used symbols T denote time interval.

Comparing the system performance (Fig. 4) for both backstepping controllers in accordance with courses shown in the figure above, following observations can be made:

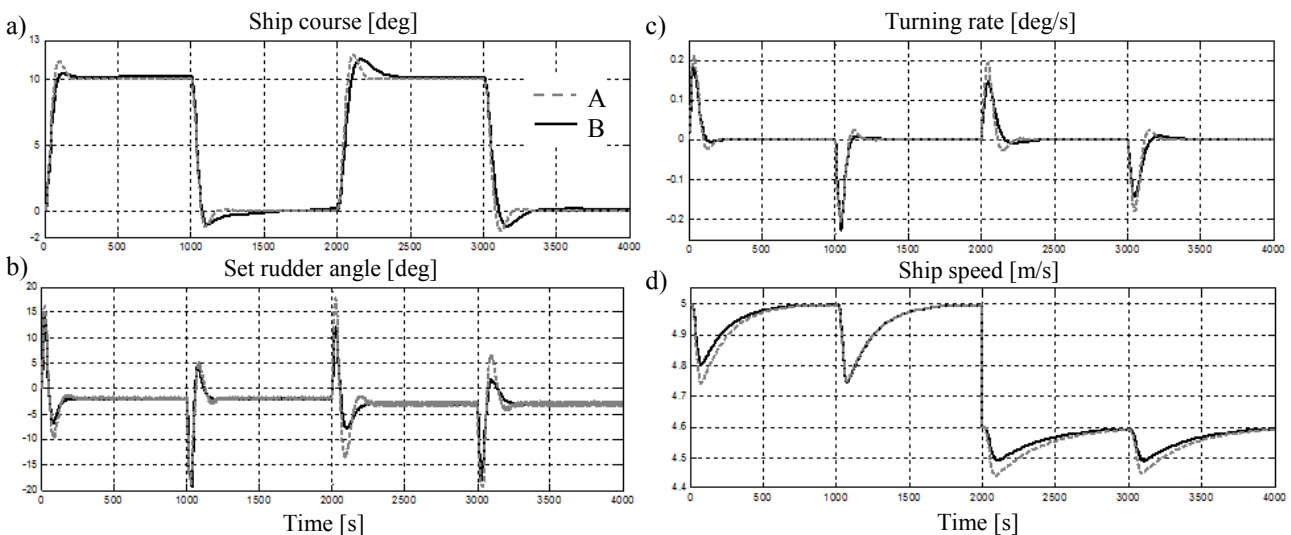


Fig. 4. Comparing results of simulation with nonlinear controllers: backstepping – version A (dashed line), version B (solid line)
 Rys. 4. Porównanie wyników symulacji z nieliniowymi regulatorami: backstepping – wersja A (linia przerywana), wersja B (linia ciągła)

Table 4. The values of time quality coefficients for A and B version of backstepping controller
Tabela 4. Wartości czasowych wskaźników jakości dla wersji A i B regulatora backstepping

	T [s]	t_n [s]	M_p [%]	t_R [s]	ISE [%]
Ballast					
Version A	(0,1000)	43	14.0965	186	0.01161
Version B	(0,1000)	54	4.7684	90	0.01027
Full load					
Version A	(2000,3000)	48	18.8052	207	0.02187
Version B	(2000,3000)	63	15.4157	101	0.01962

- with the use of the controller – version B (Fig. 4a) the real ship course is controlled to the set-point with the maximum over-regulation of lower value, than the one achieved with the controller – version A. One can observe it in both loading states;
- taking into consideration dynamic properties of the steering gear at the design stage reduces the rudder activity during the stabilization of the ship on a desired course (Fig. 4b);
- a controller with four parameters – line B, entails manoeuvring at lower angular velocity. It denotes smaller speed loss of a ship during the manoeuvres. (Fig. 4c and Fig. 4d). Speed of the ship attains the value from before the change after ca. 700 s.

In conclusion, the controller with three parameters (version A) based on an inaccurate model of the ship that did not include dynamics of the steering gear, which in turn had adverse effects on the results of the study.

Performance analysis of the controllers

The next part of the research includes comparison in performance quality between the algorithms of backstepping control (version B) and two conventional PD and sliding mode controllers. Initially, the controllers were tuned only for equations related to dynamic properties of a ship, representing the ballasting state (tables: 3 – version B, 5 – PD, sliding mode controller). Subsequently, received values were used for steering the ship for whole operating range, i.e. in both ballasting and full load states.

Table 5. Results of tuning settings for nonlinear controllers (11), (17)
Tabela 5. Parametry nastawne regulatorów (11), (17)

		Ballast		
PD	K_p	K_D	ISE	
	6.2561	250.0153	0.07288	
Sliding mode	ϕ	η	ISE	
	1.3685	0.19289	0.06351	
Full load				
PD	K_p	K_D	ISE	
	5.0831	256.9737	0.08804	
Sliding mode	ϕ	η	ISE	
	1.6618	0.33023	0.08144	

Solid line in figure 5 represents the results of simulation study conducted to examine the controllers. The best results, regarding the value of maximum over-regulation and speed losses of the ship in the ballasting state, were achieved at the initial stage of the manoeuvre (0–100 s) with the use of the backstepping controller (Figs 5a, 5d). The PD

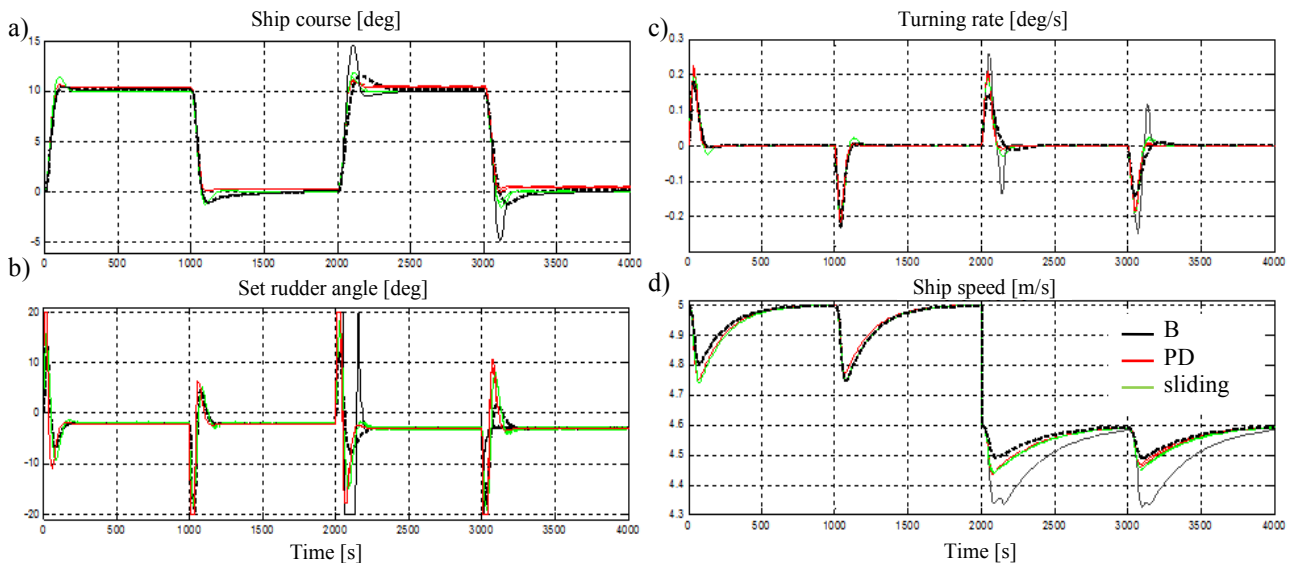


Fig. 5. Comparing results of simulation with nonlinear controllers: backstepping – version B (black line), PD (red line), sliding (green line)
Rys. 5 Porównanie wyników symulacji z nieliniowymi regulatorami: backstepping – wersja B (linia czarna), PD (linia czerwona), ślizgowy (linia zielona)

controller (Fig. 5a) helped achieve best time characteristics in the second stage of the manoeuvre (2000–3000 s) of the full loaded ship. A change in the weight of ship has significantly decreased the quality of performance of the system while the backstepping controller was used. The explanation of this observation is that the controllers had their parameters tuned only for the ballasting state and after 2000 s the parameters of the ship were changed for full load state without readjustment. It implies that the backstepping method is more sensitive to changes of the parameters of the model than sliding mode control or PD controller.

Subsequent part of the research includes re-executed simulation trial, where the controllers were tuned for both loading states (tables: 3 – version B, 5 – PD, sliding mode control). Dashed line in figure 5 depicts recorded courses.

A significant improvement in the quality of steering (lower both over-regulation and speed loss) was due to the use of backstepping controller. A constant, but small deviation from the set-point (ca. 0.2 deg – line B, 0.3 deg – sliding mode, 0.5 deg – PD) occurred during the course in all cases of used controllers. Tables 4 – version B and 6 – PD and sliding mode, include accurate time values of quality coefficients. These values were achieved based on the courses with the controllers tuned for both loading states.

Table 6. The values of time quality coefficients for A and B version of backstepping controller

Tabela 6. Wartości czasowych wskaźników jakości dla regulatora PD i ślizgowego

	T [s]	t_n [s]	M_p [%]	t_R [s]	ISE [%]
Ballast					
PD	(0,1000)	43	6.8333	75	0.03958
Sliding mode	(0,1000)	47	11.7968	77	0.03372
Full load					
PD	(2000,3000)	47	10.2536	79	0.10021
Sliding mode	(2000,3000)	54	15.0919	86	0.04489

Conclusions

The most significant factor during the stabilization of the ship on a set course or a voyage in the open sea is reduction of economic losses, e.g. fuel consumption. On merchant ships, there is a tendency to minimize fuel consumption by reducing the speed losses. Assumed quality coefficient of steering system assists the achievement of aforementioned objective. According to study results, one

can observe that lower percent value of the coefficient is attained in the course of simulation using the controller – version B, which takes into account dynamic properties of the steering gear. This occurs in both cases of ballasting and full load state. The backstepping version controller takes into account dynamic properties of the simplified steering gear at the design stage. This enlarges the number of the recurrence. The additional step increases the computational complexity of the backstepping algorithm (large number of uncertainties and complex adaptation law). However, it can contribute to the increase in the system performance.

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