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The Use of Backstepping Method to Ship Course Controller

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ABSTRACT: The article systematises and perform approaches the new concept of the ship autopilot in which control rules are derived for nonlinear controllers designed with the aid of the backstepping method and used for controlling the ship's motion on its course. The objectives, approaches and problems were described. The design is very interesting has goals to create closed-loop systems with desirable stability properties in the regulation and tracking problems with a uniform asymptotic stability, rather than analyze the properties of a given system. The symulation were performed on the tanker model and were comparised in the system with PD controller.

1 INTRODUCTION

In marine navigation, it is required the skills of determination of ship position, appointment of proper ship course as well as the keeping on appointed course. Numerous investigations performed in the past were oriented on designing an integrated ship control system. Despite significant improvement in automation, the course control is still an active field of research, especially in low speed regimes. The navigation at this speed is difficult due to manoeuvring problems connected with a relatively big mass of the ship and limited dimension of the rudder, which must be significantly deflected to obtain the required change of ship's course. This effect is especially noticeable on tankers. Reduced controllability of those ships can be compensated by the use of automatic control systems, which change the course of the ship in a desired way by proper movements of the rudder.

Nowadays, autopilots installed on ships usually use the algorithm of PID controller. The measured ship course is compared with the required (set) value and the calculated difference makes the input signal passed to the controller. The control signal, obtained at the output of the controller, is then transmitted to the servo-mechanism of the steering gear and provokes a required change in the rudder deflection angle. The automatic ship course control system (autopilot) is expected to execute two tasks. The first task consists in course changing when the ship moves along the desired trajectory, and in this case the manoeuvre should be performed fast and precisely. This is of especial importance when the maneuveres are performed in high-traffic water regions, or in restricted waters. The second task consists in keeping the ship on the desired constant course – in this case the rudder activity and the so called "ship yawing effect" should be minimised to reduce fuel consumption. The article systematises and perform an approach of the new concept of the ship autopilot in which control rules are derived for nonlinear controllers designed with the aid of the backstepping method and used for controlling the ship's motion on its course. The design sets is very interesting has goals to create closed-loop systems with desirable stability properties in the regulation and tracking problems with a uniform asymptotic stability, rather than analyze the properties of a given system, because systems that posses it can deal better with perturbations and disturbances.

Therefore the method backstepping matter first of all in the ship automation , in which were required the stability of work of arrangement as well as safety of ship quidance of on appointed course aside from of influence the disturbances and perturbances. It deal tanker ships, container as well as passenger ship.

2 BACKSTEPPING METHOD

2.1 *Historical outline*

The difficulties observed in ship control mainly result from neglecting nonlinear dynamic characteristics and changes in ship motion parameters. Numerous attempts, published in the literature, to overcome these difficulties make use of methods that linearise the system for certain operation points, like the feedback linearisation method, for instance. These methods, however, return solutions which are not fully satisfying and the linearized systems do not reflect the true proprieties of real object.

In recent ten to twenty years a number of new methods were developed for designing controllers to control nonlinear dynamic systems. These are mainly recursive methods, such as backstepping, forwarding, and various combinations of them. A common concept of the abovenamed basic recursive methods is the design of a globally stable control system, having a cascade structure, for a class of nonlinear dynamic systems. In particular, the backstepping method is based on the Lyapunov function theory (La Salle 1966) but its origin can be found in some theories of linear control, such as the feedback linearisation method or the LQR method.

The beginning of development of the backstepping method in application to nonlinear control system designs can be dated on the turn of Eighties and Nineties of the last century. A list and discussion of publications issued in that time can be found in an overview by Kokotović and Arcak (Kokotovic 2001), as well as in Fossen (Fossen 2002).

The backstepping method is based directly on the mathematical model of the examined system, introducing to it new variables in the form depending on the state variables, controlling parameters, and stabilising functions. The task of a stabilising function is to compensate non-linearities recorded in the system and affecting the stability of its operation. The linearisation methods used in the feedback-based systems usually aim at eliminating non-linearities existing in the system. The use of the backstepping method makes it possible to create, in an arbitrary way, additional nonlinearities and introduce them to the control process to eliminate undesirable nonlinearities from the system (Fossen 1998). This is of high importance in case of ship control systems in which removing all nonlinearities would require the information on accurate models of all existing non-linearities, hardly available in practice. The backstepping method allows to obtain global stability in cases when the feedback linearisation method only secures local stability.

One of the earliest books on backstepping control methods was published by Krstić, Kanellakopoulos and Kokotović (Krstic 1995). In there, especial attention was paid to adaptive and nonlinear control of SISO-type systems, with some extension to MIMO-type systems. Another concept how to apply the backstepping method in control system design was proposed by (Sepulchre 1997). The method developed by him took into account acceleration increment inertia for cascade control systems. (Krstic 1998) extended the topic, focusing on the stabilisation problem in stochastic nonlinear systems.

2.2 *The backstepping approaches*

The backstepping method was used in numerous engineering applications, among other cases for designing a system that controls the flight trajectory (Harkegard 2003), in the spaceship observation process (Krstic 1999), in the designs of industrial systems, electric machines and nonlinear systems of wind turbine-based power production, as well as in robotics for controlling a robot moving along a desired trajectory. In particular, the backstepping method can an be an effective tool in adaptive control designs for estimating parameters, (Fang 2004, Jiang 2002) and solving various optimal control problems. Moreover, the control algorithms based on the backstepping method make it possible to design a robust, nonlinear controller that limits the effect of disturbances acting both in deterministic and stochastic manner (Do 2004, Skjetne 2005). As a result, a control process is obtained which is globally stable in the entire area of its operation.

In the marine technology, the presented backstepping method was used in the systems that steer the ship on its course (Do 2004, Pettersen 2004), to secure course stabilisation. In 1999, Fossen published a work (Fossen 1999), which focused on practical use of the backstepping method in mechanical systems and its application to ship steering.

2.3 *The optimization of the system designed by backstepping*

However, attempts to apply backstepping method this method in real marine systems revealed numerous problems which needed solving. One of them is the structure and selection of the stabilisation functions and identification of their parameters. In order to obtain optimal quality of control for the designed nonlinear course controller, its parameters need tuning. 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 design systems, presented in the literature, that make use of the backstepping method are optimised using classical methods, usually based on the H^{∞} method and solution of Hamiltonian Jacobi Bellman Equation and the Riccati equation (Ezal 2000; Krstic 1999).

In the symulations performed in this article the parameters of the nonlinear control structure were tuned to optimise the operation of the control system. The optimisation was performed using genetic algorithms.

3 STRUCTURE OF CONTROL SYSTEM

For convenience, backstepping have been introduced using a system consisting of a nonlinear subsystems and a integrator chain. However, these procedures are applicable to larger classes of systems. In backstepping method arduous and time-consuming calculations were introduced therefore in this article was limited to performance the symulations results for this method only (Krstic 1995).

In present work backstepping method was applied in system showed on Figure 1. In the window „Ship" the equations of the ship dynamics characteristics were modelled. In the present investigations, the mathematical model of the dynamical characteristics of the ship was taken from a model tanker described by Astrom and Wittenmark in „Adaptive Control" (Astrom 1989) and modelled by a nonlinear third-order differential equation, referred to as the Bech and Wenger's model. The model was complemented by the dynamics of the steering gear, shown in Figure 2.

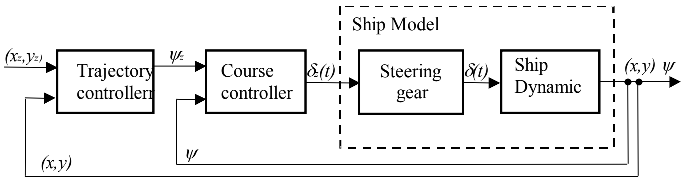

Fig. 1. The block scheme of arrangement of steering the movement of ship

The input signal passed to the steering gear comes from the autopilot and has the form of the set rudder angle, $\delta_z(t)$, while the output signal is the current rudder angle, $\delta(t)$. For the majority of ships the rudder angle and speed of its change are kept within certain limits (Amerongen1982) where $\delta_{\max}$ = 35 [deg], 2.3 $\leq \dot{\delta}_{\max} \leq$ 7 [deg/s].

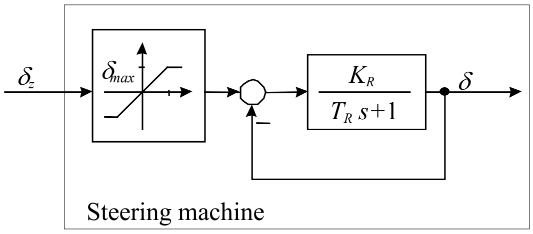

Fig. 2. The block scheme of steering gear

It is usually required for the steering blade to move from one limiting position to the other in time shorter than 30 [s]. In this article it was assumed that the rate of rudder motion is approximately limited to $\dot{\delta}_{\max} = 6$ [deg/s] until $|\delta_z - \delta| \leq 3$ [deg], when the rudder operates in the linear region of the characteristic. The maximum rudder angle is $\delta_{\max}$ = 35 [deg] .

In the window „Course controller" the ship course controller was placed.. It was accepted in system constant speed equal 5 [m/s]. The tanker model is led along the course defined by the turn points, which was used to computation the angle of ride sets among present position of tanker and the closest point of turn. 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. On Figure 1 the (x, y) they are the current co-ordinates of position of tanker got from GPS however the (x_z, y_z) they are the co-ordinates of point of turn. The controller of trajectory makes possible manoeuvring the ship in reference to position. The procedure backstepping used to design of nonlinear functions describe the structures of applied controllers was exactly performed in article (Witkowska 2007) and in this article was developed on trajectory controller.

4 SIMULATION RESULTS

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 algorithm working conditions.

Figure 3 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, 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 on a Figure 3 the exact values of the time quality coefficients, determined from the step response of two controllers for two load states, are collected in Table 1-2, 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 1. Estimated values of time quality coefficients for balasting state

	Ballasting state			
	t_n	M_p	t_R	J_c
	[s]	[%]	[s]	[-]
PD	170.68	0.81	308.15	268.6663
Backstepping	131.71	0.18	261.77	233.9747

Table 2. Estimated values of time quality coefficients for full load state

	Full load state			
	t_n	M_p	t_R	J_c
	[s]	[%]	[s]	[-]
PD	148.34	3.29	508.38	156.2852
Backstepping	115.09	18.00	439.77	154.307

Figure 4 presents an example ship trajectory with the beginning at point (0,0) and the initial ship course $\psi_0 = 0$ [deg]. Figure 4 compare trajectories for two 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. The tanker model is led along the course defined by the following turn points. The successive turning points are marked in the table by circuit.

On Figure 5, there are the temporary graphs of variables occurrent in process steerings on trajectory from Figure 4 {they were noted two ride set - for arrangement with PD controller (dashed - dot line); for arrangement with backstepping controller (dashed line) ,as well as the answering them real rides of ship: PD (dotted line), backstepping (solid line).

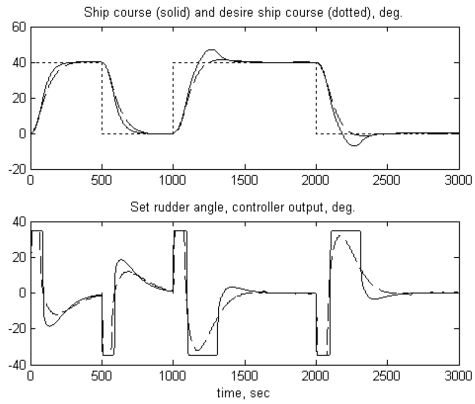

Fig. 3. Comparing results of simulation with controllers: PD (dashed line), nonlinear backstepping controller (solid line)

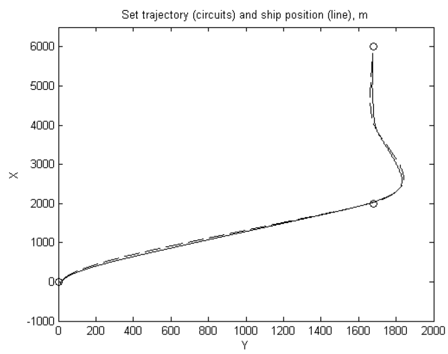

Fig. 4. Ship position along the set trajectory (circuits) - comparing results of simulation with tuned controllers: PD (dashed line), nonlinear backstepping controller (solid line)

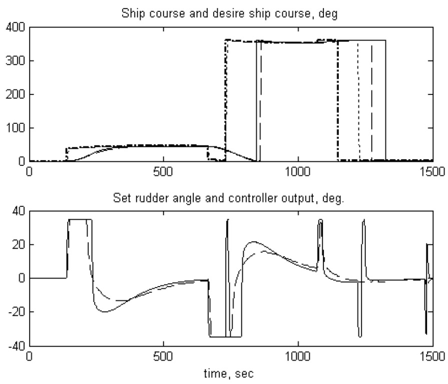

Fig. 5. Ship courses and ship rudder angles for trajectory from Figure 4

5 CONCLUSION

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.

On the ground the simulating investigations it is possible to affirm with proposed arrangement automatic the steerings the ship to possibly efektywnie practical to manoeuvring with oiler in operations of change of ride and the tailing of trajectory. The conducted investigations proved, that the arrangements of automatic steering the movement of ship from used the backstepping method are effective and with success very they can replace manual tanker control.

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