Control of the Vessel Course using of PID-Regulator under Parametric Uncertainty

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Abstract. The work is devoted to the problem of ensuring the safe movement of vessels in maritime waters. A special place within the framework of this problem is occupied by the task of planning the shipping route: the trajectory of the vessel’s movement in the local sea waters area and shipping route from the port of sailing out to the port of destination. The purpose of planning the vessel’s trajectory in the local sea waters area is to ensure navigation safety in the conditions of collective movement and geographical features of the waters area. In the present work the task of controlling the vessel when she is proceeding by the program trajectory is considered. The article notes that the inaccuracy of a preconceived ideas about the model of vessel movement can significantly affect the behavior of the vessel in the control processing, accuracy of control may become insufficient in circumstances of high traffic intensity, which can lead to dangerous approach of vessels. To solve this problem, it is proposed to include in the ship's control system the PID - regulator operating on a deviation from the course, integral from this deviation and its derivative, and also, the function of identifying the model of motion of an object by the method of speed gradient, realizing a closed system. As a model of the vessel’s movement adopted well known model Nomoto of second order. The article is accompanied by the results of modeling the proposed ship control system. It is shown that it is able to operates within a single process in real time and respond adequately to changes of motion model parameters.

1. Introduction

Ensuring the safety of vessel traffic is an up-to-date, complex and multi-aspectual problem that constantly attracts the attention of researchers. As part of this problem, the tasks of planning the shipping route - the trajectory of a vessel’s movement in a local waters area - are highlighted, the purpose of which is to ensure marine navigation safety in the presence of obstacles and in conditions of collective movement [1, 2].

Movement along a given trajectory is associated with the solution of the well-known problem of choosing the necessary speed and course of the vessel with regard to the dynamic characteristics [3]. The main difficulty in solving of this problem is related to the fact that speed and course control is not carried out directly, but by selecting the engine operating run mode, the position of the rudder blade, and for some types of ships - and the operating parameters of special additional steering devices. Under condition of unstable modes of movement, the dependence of speed and course on the operating...
parameters of the ship’s controls is complex and difficult to identify. Navigation in the storm weather and wave disturbance conditions is accompanied by rolling and yawing, drift from the current and the wind, which further complicate the vessel’s implementation (retention) of the charted trajectory, to hold plotted course.

The synthesis of the control law in the problem under consideration is related to the dynamics of the vessel and the disturbances acting on her using models of various degrees of completeness. The well-known complete mathematical model of the spatial motion of a vessel contains twelve nonlinear differential equations and is not very suitable for the study of control systems [4, 5]. Its analysis is so complex that it does not allow restoring the general picture of the motion control processes.

The synthesis of control using simplified models leads to simpler structural solutions available for technical implementation. One approach to such a simplification is a separate analysis of the elementary movements of the vessel [6]. This allows you to select for independent research from the overall spatial movement of the rolling, pitching and surge of the ship, movement along, the yaw of the ship and swaying displacement. Each of these elementary motions is described by a differential equation of the second order, whose solution is well studied [6].

The classic task of controlling the movement of the vessel is her stabilization on a charted course. Keeping the ship on a plotted trajectory is carried out by working out in one way or another method the corrections to a given course, which is assumed to be equal to the course angle of the path section, and stabilization on this adjusted course. At the same time, sufficiently accurate knowledge of her model is necessary and the synthesis of a qualitative control system requires the solution of the parametric identification problem [7]. The inaccuracy of a preconceived ideas about the model of movement of the vessel can significantly affect the behavior of the vessel in the handling process. The accuracy of such control may not be sufficient in conditions of high traffic intensity, where it can lead to dangerous convergence of ships [8].

Even if the movement model of the vessel is well identified during the sea trials, her characteristics can significantly change during operations (change in hull geometry, formation of growths on the hull, change in displacement, etc.).

A promising way to improve the quality of control is the inclusion in the control system of a proportional-integral-differential (PID, proportional-integral-derivative, PID) regulator that implements the control of course deviation, the integral of this deviation and its derivative [4, 5].

Specifying (identifying) the model of movement of the object and adjusting the parameters of the regulator as part of a single process in real time, we will have a closed vessel control system that adequately responds to changes in the parameters of the model of her movement.

This article deals with the task of controlling the course of a vessel’s movement without regard to external interference. The control action is carried out using the rudder blade. The quality criterion, according to the established tradition [3], is minimization of the turnaround time of the vessel and minimization of the number of the turning the helm. The aim of the work is to simulate and evaluate the characteristics and characteristics of ship control systems, including the PID- controller.

2. Basic model presentation

Staying within the framework of traditions, as a model of ship movement we will use the second-order Nomoto model [9], which has the form

\[ T_1 T_2 \dot{\omega} + (T_1 + T_2) \ddot{\omega} + \omega = K (\delta + T_0 \dot{\delta}) \]  

(1)

Here, the coefficients \( T_0, T_1, T_2, K \) are the constants, \( \omega \) - is the angular velocity of the vessel (the yaw rate), \( \delta \) - is the angle of rotation of the rudder blade. The peculiarity of this model is that its constant parameters have a high degree of uncertainty.

Let the ship's control system consist of a regulator, a drive and a gyrocompass and has the structure shown in Figure 1.
The desired course is fed to the entrance of the ship's course control system - \( \varphi_0 \) (Fig. 1). The difference of the actual course \( \varphi \) and the desired course \( \varphi_0 \) is a certain deviation \( \varepsilon \). The regulator needs to develop a control action \( u \), such as to minimize this deviation. Based on the control action \( u \), the actuator changes the position of the rudder blade \( \delta \), thereby changing the course of the vessel.

The transfer function of the link describing the dynamics of the vessel, in accordance with formula (1), has the form:

\[
P(s) = \frac{\omega(s)}{s\delta(s)} = \frac{\varphi(s)}{\delta(s)} = \frac{K(T_0s + 1)}{s(T_1s + 1)(T_2s + 1)}
\]

The drive (steering gear) is modeled as an integrating link, with a single negative feedback, its transfer function is:

\[
R(s) = \frac{1}{T_Rs + 1}
\]

To measure the yaw angle, a gyrocompass is used, the mathematical model of which is recorded as a first-order aperiodic link with a transfer function:

\[
H(s) = \frac{1}{T_Hs + 1}
\]

The general model of the control system with the PID controller is shown in Figure 2.

**Figure 1.** Block diagram of the vessel course control system.

**Figure 2.** Control system model with PID – controller.

The model consists of the following blocks: 1) Constant - sets the angle of turnaround of the vessel; 2) PID controller - PID controller that generates a control action; 3) Drive - a unit that simulates the operation of the drive; 4) Dead Zone - a block that sets the dead zone; 5) Ship - a unit that simulates a ship; 6) Girocompass - a unit that simulates the operation of a gyrocompass; 7) Zveno - integrating link.
For adaptive identification of vessel motion parameters, a well-known velocity gradient algorithm is used [10]. We introduce the state vector of the system \( w = (\omega, \dot{\omega})^T \), which includes the angular velocity and acceleration of the vessel. The equation of motion of the vessel (1) we write in the form characteristic of the method of speed gradient
\[
\dot{w} = Aw + \delta B
\]  
(5)
where \( A \) and \( B \) are matrices with coefficients
\[
A_{11} = \frac{-1}{T_1}; \ A_{22} = \frac{-1}{T_2}; \ A_{12} = -\frac{K}{T_2}; \ A_{21} = 0;
\]
\[
B_1 = \frac{K}{T_0}; \ B_2 = (K-1)\frac{1}{T_0}.
\]
Let at some stage of tuning (iteration with number \( m \)) system (5) look like
\[
\dot{w}_m = A_m w_m + \delta B_m + v,
\]
where \( v \) - is the vector of auxiliary signals, which allows speeding up the process of setting parameters [10].
Let \( E = w - w_m \) - be the vector of the discrepancy between the real and supposed state of the system. Introduce the objective function of the problem of adaptive identification
\[
Q = \frac{1}{2} E^T E
\]
Its derivative will be
\[
\dot{Q} = E^T ((A - A_m)w + (B - B_m)\delta - v)
\]
The partial derivatives of the last function on the model's customized parameters will be
\[
\frac{\partial \dot{Q}}{\partial A_m} = -Ew^T \quad \frac{\partial \dot{Q}}{\partial B_m} = -E\delta^T
\]
As a result, the algorithm for adjusting the parameters of the model using the velocity gradient method can be written in the form:
\[
\dot{A}_m = -\gamma Ew^T, \quad \dot{B}_m = -\gamma \delta E, \quad v = v_0 \text{sign}(E),
\]
where \( \gamma \) and \( v_0 \) are positive numbers that define the speed of adaptation of the parameters to be adjusted. The described algorithm stably converges at the values of model parameters characteristic of practice [11].

3. Numerical simulation results
A numerical simulation of the task was performed for the case of a typical fishing boat. Were taken parameters of the boat PC-450 "Uraganny" with a LoA of 24m, a Width of 7.8m and a Tonnage of 65mt. Its initial parameters of the Nomoto model are obtained from the results of field tests by observing the transient process at the left turn in the ballast and have the values
\[
T_0 = 4.0, \ T_1 = 1.0, \ T_2 = 6.0, \ K = 0.25.
\]
In this case, the transfer function (2) will be:
\[
P(s) = \frac{s + 0.25}{6.0s^2 + 7.0s + 1.0}.
\]
The existing rules for the classification and construction of vessels [12] impose restrictions on the speed-of-response of the steering gear. Depending on its type (mechanical, hydraulic, electro-hydraulic, etc.), the rules set the minimum angular speed of the turning the helm. In this work, the angular velocity of the turning the helm is assumed to be 4 degrees per second, which corresponds to the value \( T_R = 0.25 \).
When modeling it is assumed that the gyrocompass has a low inertia, we take the value. $T_H = 0.6$. Thus, the transfer functions (3), (4) will have the form

$$R(s) = \frac{1}{0.25s + 1}, \quad H(s) = \frac{1}{0.6s + 1}.$$  

There are a large number of PID - controller tuning methods [13]; an analytical tuning method is used for the parameters of the simulated ship model. The control objective is a smooth transition with a small overshoot value. The dependence of the control action of the PID- controller on the deviation $\varepsilon$ (between the desired and the actual course) is described by the equation:

$$u(t) = K_p \varepsilon(t) + K_i \int_0^t \varepsilon(s) ds + K_d \frac{d\varepsilon(t)}{dt}.$$  

Configuring the PID-controller with an analytical method gives the following parameter values: $K_p = 2.455$, $K_i = 0.093$, $K_d = 2.458$.

Two cases are simulated: turning the vessel by 5 degrees with accurate knowledge of the model (1); turn of the vessel by 5 degrees in the conditions of the inaccuracy of a preconceived ideas about the parameters of the model (1).

In figure 3 shows the result of modeling the steering action of the vessel by 5 degrees with accurate knowledge of the model (1).

![Figure 3](image-url)  

**Figure 3.** Results of vessel control simulation (5 degrees turn). 1- is a control signal from the control controller, 2- is the angle of the rudder blade steering action, 3- is the change in the course of the vessel.

From the graphs (Figure 3) it can be seen that when using the PID-controller, the course is smoothly adjusted for 25 seconds, at the beginning the PID-controller issues a control signal with the steering wheel turning 13 degrees, thereby making a quick turn and then a smooth adjustment for the commanded course. This model does not take into account the relay component of the change in the steering position, i.e. a simplified model of the steering gear is used.
Now let us simulate a situation in which the parameters of the vessel have changed slightly (the geometry of the vessel's hull has changed, the bottom has become overgrown with shells, etc.). Reflect this by changing the time constant in the transfer function of the vessel without reconfiguring the controllers, so that the transfer function of the vessel takes the form:

$$P(s) = \frac{s + 0.5}{6.0s^2 + 7.0s + 1.0}$$

In figure 4 shows the result of modeling the steering action of the vessel by 5 degrees under the conditions of such the inaccuracy of a preconceived idea about the parameters of the model (1).

![Figure 4](image_url)

**Figure 4.** The results of the simulation of the control of the vessel in terms of the inaccuracy on the model of movement (steering action of 5 degrees). 1 - control signal from the controller of control, 2 - angle of rudder blade, 3 - change of course of the vessel.

From the graphs in Figure 4, it is clearly seen that the vessel makes a steering action of about 20 seconds, while for quite a long time the course of the vessel fluctuates relative to the desired one. With increasing angle of steering action of the vessel the difference will be even more noticeable. More "sharp" behavior of the PID-controller is associated with its differential component. The graphs clearly show that the system assumes an oscillatory character, thereby significantly increasing the number of rudder shifts (graph 2 in Figure 4). The using of a PID-controller in conditions of strong disturbing influences or with significant parametric uncertainty can lead to complete loss of stability in handling. Thus, it seems appropriate to identify the model of the vessel.

In figure 5 shows the implemented scheme of the adaptive identification algorithm. Here, 1- is the block generating the master signal; 2 - ship model; 3- block adaptive identification of the model; 4- is a block showing the output signal of the object and the model being configured; 5 - block showing the difference (discrepancy) of the output signal of the object and model (E).
Figure 5. System of adaptive identification of parameters.

In figure 6 shows the simulation results of the ship model identification process. The values of the discrepancy between the real and expected state of the system (E) in the identification process are shown, Graph 1 shows the difference between the angular velocity of the object and the angular velocity of the tuned model, graph 2 shows a similar difference in accelerations. It can be seen that after only 5 seconds, the identification error becomes close to 0. Such a time interval is quite acceptable for practice.

Figure 6. The results of the identification model of the movement of the vessel.

The updated ship model is used to adjust (reconfigure) the parameters of the PID-controller. Its implementation with the current values ensures stability and improves the quality of control.

In general, the simulation results demonstrate the constructiveness of the proposed integrated scheme of the ship control system.

4. Conclusion

When implementing a ship control system, the controller's parameters take into account the known dynamic characteristics of the vessel. Over time, these characteristics can change significantly (fouling, deformation of the hull, change in loading, etc.), which, in turn, significantly affects the quality of control. The control system must be either adaptive, able to adapt to the changed conditions, or be able to adjust the control parameters manually.
The paper proposes a ship control system using the classical PID controller. Implemented an algorithm for adaptive identification of control system parameters based on the gradient approach for the 2nd order Nomoto model. The described parametric identification can be performed both in real time and using previously saved data (offline). To assess the degree of change in the parameters of the mathematical model of the vessel, the identification process can be carried out under various conditions. The best results are obtained by the active maneuvering of the vessel, for example, the movement of the "zigzag" type with intensive re-steering of the rudder blade.

The results of the work are focused on expanding the functionality and improving the quality of operation of ship control systems.

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