The method for automatic control of a ship with directional instability

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Abstract. A method for creating an automatic control system for a ship with directional instability has been developed. As part of the tests of a small-sized unmanned vessel, a control diagram was built. It showed that the vessel is unstable along its route. It became necessary to add a control channel for the angular acceleration of the vessel to the main channels of the PID regulator. The PID-U regulator has a significant advantage in controlling an unstable vessel on the route over a standard PID regulator due to the channel of angular acceleration; the regulator monitors the angular speed and compensates it with control actions. The disadvantage of the method is difficulties in finding the angular acceleration of the vessel, since, gyroscopic sensors installed on vessels provide data only on the route and angular speed. Simple integration of the angular speed to determine the acceleration can result in errors, especially in wind-wave conditions. The mathematical observer based on the Kalman filter can be used. The results of operation modeling for this regulator are described.

1. Introduction
Unstable vessels are a special case of navigation practice. An unstable vessel [1], deviating from the course, almost always tends to deviate further and requires a sharp and large shift of the rudder to compensate for the dynamics of deviation. Yawiness is inherent in ships with full contours, small length-to-width ratios, shallow draft and bow trim. However, under certain conditions of loading and environment, damage to the rudder complex and other factors unfavorable for navigation, any vessel can become unstable. Thus, considering an unstable ship as an object of control, we can say that a broader and more general case of ship control is being investigated.

2. Material and methods
Based on the results of sea tests ("spiral" maneuver) of the unmanned vessel, the kinematic data shown in Figure 1 were obtained.

It can be seen that with a stepped rudder shift, a ridge of overshoot of the angular speed appears before it takes on a steady-state value, and steady-state angular speeds are not proportional to the rudder shift angles that cause them.

The first fact suggests that the order of the model should not be lower than the second. The second fact indicates that the use of standard first and second order Nomoto models is impossible, since they require a linear dependence of the steady-state values of angular speeds on the rudder shifts that cause them.
Figure 1. Dependence of the angular speed of the vessel on the rudder angle

It is proposed to use an interconnected model for the angular and translational speeds as a reference identification model, taking into account the effect of drop in the forward speed on the controllability of the vessel:

\[
\begin{align*}
\dot{\omega} &= \frac{1}{T_1} \omega + k_1 \nu \delta; \\
\dot{\nu} &= \frac{1}{T_2} \nu + k_2 \omega^2 + k_3 n,
\end{align*}
\]

where \(T_1, 2\) – model’s time constants; \(\omega, \nu\) – angular and longitudinal speeds; \(\delta, n\) – rudder angle and propeller speed; \(k_1, 2, 3\) – model’s coefficients.

Figure 2. Transient model’s processes.
When modeling equation (1) with parameters: $T_1 = -2.5$, $T_2 = -1.4$, $k_1 = 0.5$, $k_2 = -0.005$, $k_3 = 0.001$, the transient control processes take the form shown in Figure 2. The relative error of the angular speed of the mathematical model does not exceed 5%, which indicates the correctness of the choice of the model (1) and coefficients.

![Figure 3. Ship model handling diagram (1). $\omega_c$—steady-state angular speed at the corresponding rudder angle.](image)

It is proposed to simulate transient control processes of an unstable ship using the standard PID regulator with a differential channel filter (in the form of a transfer function) (2) and an extended PID regulator (PID-U) (3) supplemented by an angular acceleration channel [2].

\[
\delta = P + I \frac{1}{s} + D \frac{N}{1 + N \frac{1}{s}};
\]

(2)

where $P = 10; I = 0.002; D = 1500; N = 2$ – PID regulator parameters.

\[
\delta = a_p \Delta \Phi_p + a_i \int \Delta \Phi_p dt + a_d \omega + a_{dd} \dot{\omega};
\]

(3)

where $a_p = 4; a_i = 0.002; a_d = -280; a_{dd} = -3000$ – PID-U regulator parameters; $\Delta \Phi_p$ – deviation of the current route value from the set one.

The quality of control is assessed by a generalized integral criterion for deviation and control:

\[
Q = \int (\Delta \Phi + \delta) dt;
\]

3. Results and discussion

The simulation results in the MATLAB environment [3] are presented in Figures 4 - 6 (kinematic parameters, control actions and a control quality criterion for PID and PID-U regulators with the limitation of the rudder shift at 15 and 30 degrees of the left and right sides and deviation of the route from 0° to 30°.)
Figure 4. Transient control of the ship along the course.

Figure 4 shows that the standard PID regulator with optimal settings generates a control signal that forms an oscillatory transient; the PID-U regulator ensures an aperiodic process that improves the control quality.

Figure 5. Control actions on the ship.

Figure 5 shows that the standard PID regulator compensates for the allowed overshoot by the rudder shifts to the maximum allowable value. The PID-U regulator does not allow overshoot with a permissible maximum rudder shift of 30°, and when the shift is limited to 15°, it compensates for a single overshoot by 8° rudder shift.
According to the proposed quality criterion, the best control was shown by the RPID regulator with a preset maximum rudder deflection of 30° for each side. The quality of control of the standard PID regulator, which is unstable along the ship’s course, turns out to be unsatisfactory at any settings.

4. Conclusion
Thus, the PID-U regulator has a significant advantage in controlling an unstable vessel due to the additional channel of angular acceleration of the vessel; the regulator monitors the angular speed and compensates it with control actions. The disadvantage of the method is difficulties in finding the angular acceleration of the vessel, since gyroscopic sensors installed on vessels provide data only on routes and angular speed. Integration of the angular speed to determine the acceleration can result in errors, especially in wind-wave conditions. However, the mathematical observer based on the Kalman filter can be used. Thus, the proposed autopilot can use a mathematical estimate of the angular acceleration parameter obtained with the help of this observer.

References
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