Development of a Ship's Course Controller using μ-synthesis

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Abstract: - The article describes the procedure for designing a robust controller for controlling the course of sea vessels exposed to sea waves using μ-synthesis. To this end, practical knowledge of the vessel is used to obtain a linear design model with parametric uncertainties describing the dynamics of the vessel. Appropriate frequency weighting functions are selected to provide the required performance characteristics during the controller design phase. The proposed model and then the weighting functions are used to design a robust controller. The problem of wave filtering in the low-frequency range is also considered during the modeling and design of the controller. The key contribution of the paper is that it provides system designers with a methodology for obtaining uncertain linearized ship models that naturally fit within the framework of μ-synthesis control theory, and it describes, in a systematic manner, the various stages of the controller design process. In addition, the document contains detailed information on methods for analyzing robust systems and their modeling.

Key-Words: - robust control, uncertain dynamic models, wave filtering, sea waves, controller, μ-synthesis.

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1 Introduction

Ship heading control systems are among the basic technical systems. In addition to providing the main function, they also provide the implementation of other, more complex tasks and, in particular, control of the movement of the vessel along the route or trajectory. The wind-wave effect has a significant disturbing effect on the operation of the ship's course control system, causing a significant activation of the ship's steering mechanisms. The disturbance created by sea waves is fed to the input of the regulator, which forms a control action supplied to the input of the steering engine, which is excessively active, working out insignificant local deviations of the vessel from the course. This phenomenon is most evident in control laws that use signal derivatives.

Almost all automatic heading control systems currently used on ships use PID controllers to implement the task of automatically stabilizing the ship. Their use is justified due to their sufficient efficiency in controlling complex dynamic objects, such as sea vessels, the mathematical models of which are quite difficult to formalize.

To control marine mobile objects (MMO), modern algorithmic and software tools are used, which are included in the basis of automation devices. These devices are connected to the steering gear, which allows you to track changes in course. To do this, it is necessary to evaluate the parameters of the control system, taking into account the characteristics of the vessel's movement under the influence of exogenous disturbances (currents, waves, wind), [1]. Using effective methods for adjusting autopilot parameters will improve the quality of control and optimal performance of the vessel. Recently, a significant number of publications have appeared with developed methods that make it possible to select autopilot parameters that will ensure the suppression of various types of exogenous disturbances, [2], [3], [4], [5], [6]. The use of wave filters based on the Kalman filter is also considered, [7], [8], [9], [10], [11].

2 Problem Formulation

The theoretical basis for solving problems associated with the development and research of traffic control systems for MMO and, in particular, sea vessels, are mathematical models of control objects. One of the characteristic features of sea vessels and, in general, MMO is significant parametric and structural uncertainty associated with the specific conditions of their operation. The specified uncertainty in the mathematical model of the movement of a sea vessel leads to the need to take it into account when constructing a control system. In connection with the need to take into account the uncertainty factor of the parameters of the mathematical model of the vessel, adaptive regulators have been developed, the characteristics of which are adjusted following specific conditions, [12], [13], [14], [15]. An alternative to adaptive control of a ship as a parametric uncertain object is the robust approach, which has also been developed, [16], [17], [18], [19], [20]. The main idea of robust control is to ensure the specified quality of processes in the system for certain specified intervals of possible values of the parameters of the controlled object - the vessel, [21], [22], [23], [24], [25]. Recently, artificial intelligence methods have also been widely used to control sea vessels, [26], [27], [28], [29].

The purpose of this study is to study an approach to reducing the activity of the steering gear in rough seas by using a ship dynamics model and compensating for the influence of disturbance in a certain frequency band. The specificity of this work is that the robust regulator introduced into the control loop is synthesized taking into account the uncertainty of the ship model parameters and reduced sensitivity to wave yaw in the low-frequency region. The controller is developed using μ - synthesis, [30], [31], [32].

3 Problem Solution

The ship's control system includes a control device, a steering gear, a gyrocompass, and the ship (Figure 1).

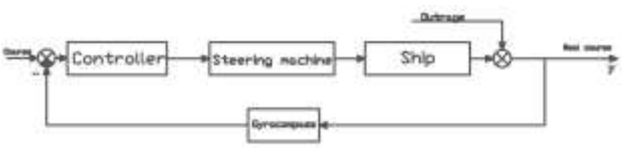

Fig. 1: General block diagram of the ship's course control system

The dynamics of a heading control system are usually studied using the second-order Nomoto model, in which the transfer function is represented as

$$W_C(s) = \frac{K_C(T_3 s+1)}{(T_1 s+1)(T_2 s+1)s} \qquad (1)$$

The parameters of the dynamic model are uncertain, as they can vary within the following limits:
$0{,}235 \ge K_C \ge 0.135$; $K_{CH} = 0.185$; $141{,}6 \ge T_1 \ge 94{,}4$; $T_{1H} = 118$; $9{,}36 \ge T_2 \ge 6{,}24$; $T_{2H} = 7{,}8$;
$22{,}2 \ge T_{3H} \ge 14{,}8$; $T_{3H} = 18{,}5$. (Time constants are given in seconds for a Mariner-class cargo ship, [33]).

For feedback design purposes, it is desirable to simplify the uncertainty model while being sure to preserve its overall variability. This is one use of the *ucover* command. This command takes an array of LTI realizations *Wa* and a nominal realization W_{CH} and models the difference Wa-W_{CH} as a multiplicative percentage control system uncertainty (*ultidyn*). To use *ucover*, we first map the uncertain W_C model to the family of LTI implementations by using the *usample* function, [30]. This command retrieves the parameter values of undefined elements in the system. It returns an array of LTI models, where each model represents one of the possible behaviors of the uncertain system.

In this case, 60 sample W_C values are generated, using a random number generator to ensure repeatability of *Warray* implementations. We then use the *ucover* function to cover all *Warray* implementations in a simple indeterminate model of the following form:

$$Wsys = W_{CH} * (1 + Wt * Delta),$$

where all the uncertainty is concentrated in the "unmodeled dynamics" - the *Delta*(*ultidynobject*) component. Let us choose the nominal value of W_{CH} as the center of the frequency response graphs and use a 3rd order shaping filter *Wt* to record changes in the relative gap between *Warray* and W_{CH} depending on frequency. After executing these commands, we find a stable approximation of the upper boundary with a minimum phase (Figure 2).

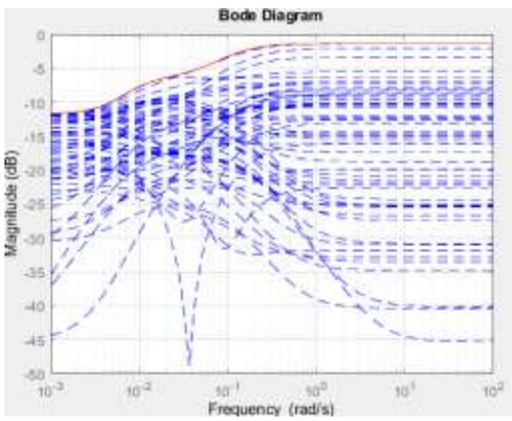

Fig. 2. Approximation of the frequency characteristics of an object with a minimum phase

The transfer function of the stable minimum-phase approximation of the multiplicative uncertainty is written as follows:

$$Wt(s)=\frac{0.8543\, s\hat{}3 + 0.05881\, s\hat{}2 + 0.0005098\, s + 1.418e-06}{s\hat{}3 + 0.118\, s\hat{}2 + 0.00146\, s + 5.5e-06} \quad (2)$$

The transfer function (2) is the result of calculations using the *ucover* command.

3.1 Creating an Open-Loop Model of the Designed System

To design a robust controller for an uncertain P setting, it is necessary to select the target closed-loop bandwidth *desBW* and perform a sensitivity minimization calculation using the simplified uncertainty model *Usys*. The structure of the control system is shown in Figure 3.

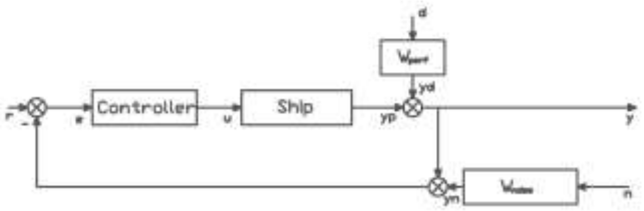

Fig. 3: Block diagram of the ship's heading control system

The main signals are the disturbance-disturbance *d*, the measured noise signal *n*, the control signal *u* and the output coordinate of the installation *y*. The *Wperf* and *Wnoise* filters reflect the frequency content of interference and noise signals, or equivalently, frequency ranges in which interference is observed and good noise suppression properties are required. Our goal is to keep *y* close to zero, rejecting noise *d* and minimizing the influence of measurement noise *n*. It is necessary to design a controller that keeps the gain from *d* and *n* to *y* as small as possible. In this case, the value of *y* is determined by the following expression:

*y = Wperf * 1/(1+PC) * d + Wnoise * PC/(1+PC) * n*

Thus, the transfer function of interest consists of performance- and noise-weighted versions of the sensitivity function *1/(1+PC)*, plus an additional sensitivity function *PC/ (1+ PC)*. Let's choose the performance weighting function *Wperf* as a first-order low-pass filter with a value greater than 1 at frequencies below the required closed-loop bandwidth:
desBW = 0.3 is the cutoff frequency desired for a closed-loop system;

Wperf = *makeweight*(300, *desBW*, 0.5).

The specified choice of the performance weighting function *Wperf* assumes the effective suppression of wave disturbances that affect the accuracy of maintaining the specified course of the vessel.

To limit the controller bandwidth and prevent going beyond the desired bandwidth, we use a *Wnoise* noise sensor model with a magnitude greater than 1 at frequencies exceeding *10*desBW*. In this case, the transfer function of the noise sensor is equal to:

$$Wnoise(s)=\frac{44.44\, s\hat{}2 + 9.427\, s + 1}{0.01778\, s\hat{}2 + 3.771\, s + 400} \quad (4)$$

Then we build an open connection of the system blocks using the Connect function shown in Figure 3, using the following expression:
M=connect(Wsys,Wperf,Wnoise,S1,S2,S3,{'d','n' ,'u'},{'y', 'e'});

3.2 Synthesis of the Course Regulator

The design controller is designed using the *musyn* automated command, an indefinite model with an open contour is set through:

M:[K,CLperf] = musyn(G,ny,nu).

This command synthesizes an unstructured robust black box controller for a system where the plant contains some dynamic uncertainty. The controller also eliminates the effects of noise on the system output. The controller transfer function obtained as a result of the calculation is of order 15, so an attempt was made to reduce its order using the reduce command. In this case, it was possible to obtain an 8th order regulator. The controller transfer function has the following form:

$$Kp = \frac{96.1s^7 + 2.042e4s^6 + 2.169e6s^5 + 6.834e5s^4 + 5.546e4s^3 + 516.8s^2 + 0.9438s + 5.154e-6}{s^8 + 885.7s^7 + 5859s^6 + 1.708e4s^5 + 2.533e4s^4 + 5460s^3 + 246.4s^2 + 0.7211s + 0.0004658}. \quad (4)$$

To illustrate the results obtained during the design process, we present the LFC and PFC of an open-loop vessel course control system (Figure 4).

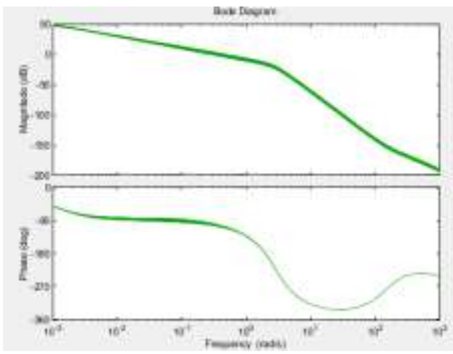

Fig. 4: Logarithmic amplitude- and phase-frequency characteristics of an open-loop system

Using the function *S= allmargin(L)*, we calculate the gain margin, phase margin, delay margin, and corresponding crossover frequencies for the SISO negative feedback loop with the open-loop response *L*. The negative feedback loop is calculated as feedback *(L,eye(M))*, where *M* is the number of inputs and outputs in *L*. In our case, using this function gives the following result:

GainMargin:5.9389e+00 GMFrequency: 1.9763e+00
PhaseMargin: 7.6413e+01 PMFrequency: 3.7192e-01
DelayMargin: 3.5858e+00 DMFrequency: 3.7192e-01

Stable: 1.

The values obtained as a result of applying the *allmargin(L)* function indicate the stability of the system under study, as well as a sufficiently large margin both in modulus and in phase. High stability is indicated by the results of checking the system using the *robuststab* function. For example, the system can tolerate up to 389% of modeled uncertainty. The sensitivity for each undefined element is: 100% for *delta_m*. Increasing *delta_m* by 25% reduces margin by 25%.

Figure 5 shows the transition function for the disturbing influence.

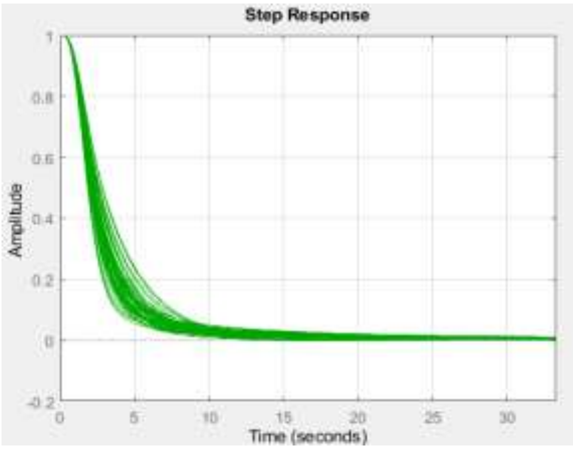

Fig. 5: Transient function of the disturbance control system

From Figure 5 it can be seen that the behavior of the transition function corresponds to the stable movement of the system, and also changing the parameters slightly changes the nature of the transition process and the time of its execution. The simulation of the proposed system for the nominal parameters of the vessel also showed that the system provides filtering of harmonic wave disturbances in the frequency range from 0.05 rad/s and below.

4 Conclusion

The proposed approach to the synthesis of a robust ship course controller has shown that it is possible to both provide the control function of a model with uncertain parameters and filter the influence of sea waves in the low-frequency region.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

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Conflict of Interest

The authors have no conflicts of interest to declare.