Synthesis of a robust controller for ship course control

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Abstract: - The article describes the design process of a robust controller for course control of a marine vessel subject to the influence of sea waves using μ-synthesis. For this purpose, practical knowledge of the vessel is used to derive a linear design model with parametric uncertainties describing the vessel dynamics. Appropriate frequency weighting functions are selected to ensure the required performance characteristics at the controller design stage. The proposed model and then the weighting functions are used to develop a robust controller with a fixed structure, which allowed us to significantly reduce the order of the designed controller. The problem of low-frequency wind-wave filtering in the controller design and in the modeling process is also considered. The key contribution of the paper is that it provides system designers with a methodology for deriving uncertain linearized vessel models that fit naturally into the framework of μ-synthesis control theory. It describes, in a systematic way, various methods for the controller design process. In addition, the paper provides detailed information on the methods for analyzing robust systems and their modeling.

Key-Words: - robust control, uncertain dynamic models, wave filtering, vessel heading control, water surface disturbance

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1 Introduction

Vessel heading control systems are among the basic technical systems. In addition to providing the main function, they also ensure the implementation of other, more complex tasks, and, in particular, control of the vessel's movement along a route or trajectory. Wind and wave action has a significant disturbing effect on the operation of the vessel heading control system, causing significant activation of the vessel's steering gear mechanisms. The disturbance created by sea waves enters the input of the controller, which forms a control action fed to the input of the steering gear, which is excessively active, processing insignificant local deviations of the vessel from the course. This phenomenon is most pronounced in control laws using signal derivatives. Almost all automatic vessel heading control systems currently used on ships use PID controllers to implement the task of automatic vessel stabilization. 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. The articles [1] - [5] consider the use of wave filters based on the filter. 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 machine, which allows tracking the course change. For this, it is necessary to evaluate the parameters of the control system, taking into account the provision of vessel motion characteristics under the influence of exogenous disturbances (currents, waves, wind) [6]. The use of effective methods for adjusting the parameters of the autopilot will improve the quality of control and optimal characteristics of the vessel's motion. Recently, a significant number of publications have appeared with developed methods that allow you to select the parameters of the autopilot that will ensure the suppression of various types of exogenous disturbances.

2 Problem Formulation

The theoretical basis for solving problems related to the development and study of motion control systems for marine vessels and, in particular, marine vessels, are mathematical models of control objects. One of the characteristic features of marine vessels and, in general, marine vessels is significant parametric and structural uncertainty associated with the specific conditions of their operation. The specified uncertainty in the mathematical model of marine vessel motion 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 controllers have been developed, the characteristics of which are adjusted in accordance with specific conditions [7] - [10]. An alternative to adaptive control of a vessel as a parametric uncertain object is a robust approach, which has also been developed [11]-[19]. The main idea of robust control is to ensure a given quality of processes in the system for some given intervals of possible values of the parameters of the controlled object - the vessel. The aim of this study is to investigate an approach to reducing the activity of the steering machine in sea rough conditions by using a model of the vessel dynamics and compensating for the influence of disturbance in a certain frequency band. The specificity of this work is that the robust controller introduced into the control loop is synthesized taking into account the uncertainty of the parameters of the vessel model and reduced sensitivity to wave yaw in the low-frequency region. The controller is developed using μ -synthesis [20]-[22].

3 Problem Solution

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

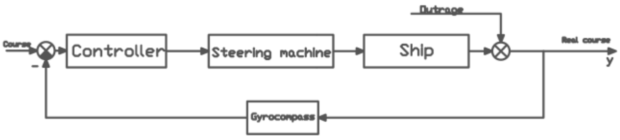

Fig. 1. General block diagram of the ship's course control system.

The dynamics of a heading control system is 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:

$0{,}235 \geq K_C \geq 0.135$; $K_{CH} = 0.185$;

$141{,}6 \geq T_1 \geq 94{,}4$; $T_{1H} = 118$;

$9{,}36 \geq T_2 \geq 6{,}24$; $T_{2H} = 7{,}8$;

$22{,}2 \geq T_{3H} \geq 14{,}8$; $T_{3H} = 18{,}5$.

(Time constants are given in seconds for a Mariner-class cargo ship [23]).

For feedback design purposes, it is desirable to simplify the uncertainty model while preserving its overall variability. This is one application of the ucover command. This command takes an array of LTI realizations *Wa* and a nominal realization *Wcн* and models the difference *Wa*-*Wcн* as a multiplicative uncertainty in the control system in percent (*ultidyn*). To use *ucover*, first map the uncertain model *Wc* to a family of LTI realizations, using the *usample* function [20]. This command samples the parameter values of uncertain 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 the case under consideration, 60 sample values of *Wa* are generated, and a random number generator is used to ensure repeatability of *Warray* realizations. Then we use the *ucover* function to cover all *Warray* realizations in a simple uncertain model of the following form

$$Wsys = Wc_H * (1 + Wt * Delta),$$

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

The transfer function of a stable minimum-phase approximation of multiplicative uncertainty is

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

3.1 Creating an Open-Loop Model of the Designed System

To design a robust controller for an uncertain plant *P*, it is necessary to select a target closed-loop bandwidth *desBW* and perform a sensitivity-minimizing calculation using a simplified uncertainty model *Usys*. The control system structure is shown in Fig. 2.

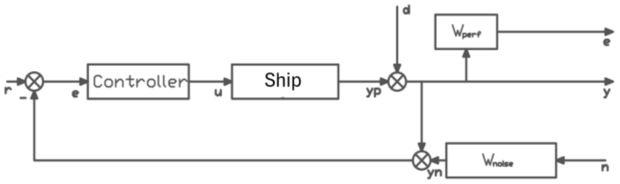

Fig. 2. Block diagram of the vessel heading control system.

The main signals are the disturbance *d*, the measured noise signal n, the control signal u and the output coordinate of the plant *y*. The filters *Wperf* and *Wnoise* reflect the frequency content of the disturbance and noise signals, or equivalently, the frequency ranges in which disturbances are observed and good noise rejection properties are needed. Our goal is to keep y close to zero, rejecting the disturbance d and minimizing the influence of the measurement noise n. It is necessary to design a controller that keeps the gain from *[d; n]* to *y* as small as possible. Note that

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

thus, the transfer function of interest consists of performance-weighted versions of the sensitivity function, noise *1/(1+PC)* and a complementary sensitivity function *PC/(1+PC)*. We select the performance weighting function *Wperf* as a first-order low-pass filter with a magnitude greater than 1 at frequencies below the desired closed-loop bandwidth:

desBW = 0.1 - the desired cutoff frequency for the closed-loop system;

Wperf = makeweight(300,desBW,0.5).

The specified choice of the performance weighting function *Wperf* assumes effective suppression of wave disturbances on the accuracy of maintaining the vessel's specified course. To limit the controller bandwidth and prevent going beyond the desired bandwidth, we use the noise sensor model *Wnoise* with a magnitude greater than 1 at frequencies exceeding *10*desBW*. The transfer function of the noise sensor is

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

Then we construct an open connection of the system blocks using the connect function, shown in Fig. 2.

M=connect(Wsys,Wperf,Wnoise,S1,S2,S3,{'d','n','u'},{'y', 'e'});

3.2 Synthesis of the rate controller

The design of the heading controller was initially implemented using the automated *musyn* command applied to an open-loop uncertain model given by

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 at the system output. The controller transfer function obtained as a result of the calculation had the 15th order, so an attempt was made to reduce its order using the reduce command, which resulted in an 8th-order controller. A more efficient reduction in the controller order can be achieved by using one of the ᴍ-synthesis methods with a robust structured controller. For this, we will use the same control structure, but restrict the controller structure to the state space model by choosing its order. We will set the order of the single-input, single-output controller using the command:

C0=tunableSS('K',1,1),

where K is the specified order of the controller. The controller is synthesized using the automated command *musyn*, applied to an indefinite open-loop model, which is specified via

M: [CL, CLperf] = musyn(CLo).

As a result of experimental calculations, a 4th-order controller of the following type was selected

$$Wp(s) = \frac{672{,}5s^4+1{,}682e05s^3+1{,}9e07s^2+6{,}07e06s+4{,}0331e05}{s^4+204{,}6s^3+4735e^2+2.621e05s+3{,}79e05}. \quad (5)$$

Since the obtained analog algorithm of the regulator operation will be practically implemented using a digital controller, it is necessary to transform it into a discrete form using analog-to-discrete transformation. As a result, for the discrete period T=0.01 s, we obtain the discrete transfer function of the regulator in the following form

$$dWp(z) = \frac{672{,}5z^4+40117z^3-8240z^2+178{,}3z+1774}{z^4-2{,}846z^2+2{,}966z^2-1{,}23z+0{,}1293} \quad (6)$$

Fig. 3 shows the Bode diagrams for the given transfer functions.

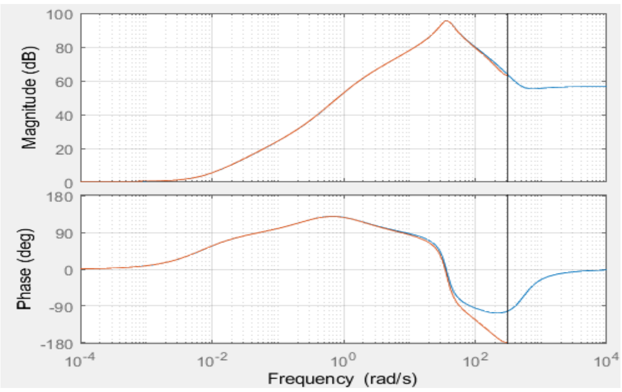

Fig. 3. Analog (blue) and discrete (red) amplitude and phase Bode diagrams.

Bode diagrams for the analog and discrete forms of representation of the transfer function of the controller show their almost complete identity, which allows us to obtain the same dynamic characteristics of the system with different forms of representation of the controller. Using the function *S=allmargin(L)*, we calculate the gain margin, phase margin, delay margin and the corresponding intersection frequencies for the SISO negative feedback loop with an 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, the application of this function gives the following result:

GainMargin:[6.0196e+00Inf];GMFrequency:[4.2442e+01Inf];

PhaseMargin: 1.1443e+02; PMFrequency: 2.6957e+00;

DelayMargin: 7.4090e-01; DMFrequency: 2.6957e+00;

Stable: 1

This indicates a fairly large margin both in modulus and phase. The high stability is indicated by the results of the system check using the robuststab function: The uncertain system is robust to the modeled uncertainty. For example, it can withstand up to 446% of the modeled uncertainty. There is a destabilizing disturbance that is 446% of the modeled uncertainty. This disturbance causes instability with a frequency of 0.0933 rad/sec. The sensitivity to each uncertain element is: 100% for delta_m. Increasing delta_m by 25% reduces the margin by 25%.

3.3 Modeling a control system with a synthesized regulator

In conclusion, we will model a control system in the Simulink program, containing the transfer functions of the vessel *Wcn*, the synthesized regulator *Wp1* and the filter *Wf* of the wave disturbance generator. The model also contains a Step setter, a white noise generator, an amplifier and three Scope oscilloscopes. The model diagram is shown in Fig. 4.

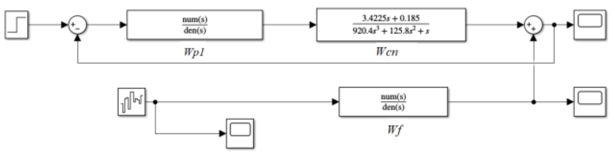

Fig. 4. Structural diagram of the ship control model.

As a shaping filter Wf we will use a transfer function simulating a random process of sea waves of 4 points of the following type [24]

$$Wf(s) = \frac{5,8408s^4}{s^8+6,092s^7+23,54s^6+49,67s^5+75,0s^4+ \\ +74,73s^3+56,2s^2+25,61s+8,428}. \quad (7)$$

Fig. 5 shows the transition function of the control system for the disturbance effect.

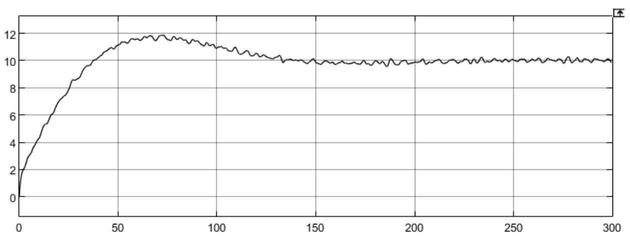

Fig. 5. Transient function of the disturbance control system.

From the presented graph it follows that the synthesized controller provides high stability and good reliability of the system operation.

4 Conclusion

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

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