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# NONLINEAR ROBUST CONTROL SYSTEM FOR STABILIZATION OF MARINE VEHICLES

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***Abstract*—*Nonlinear robust control system, that improves marine vehicle's control process under condition of a marine vehicle's and environment's uncertainty, is considered in the article. Nonlinear robust system allows to keep a predetermined optimal stabilization trajectory of a nonlinear marine vehicle in the required vicinity by creating additional robust contour that enables to compensate different types of uncertainty. Optimal speed system based on variable structure is used to determine an optimal stabilization trajectory, taking into account given dimension of the marine vehicle's model, required type of stabilization trajectories and constraints on control actions. Nonlinear robust system solves control tasks of nonlinear marine vehicles during maneuvering and dynamic positioning under condition of uncertainty.*

**Index Terms**—Marine vehicles; robust control; nonlinear control systems; variable structure.

## I. INTRODUCTION

Provision of motion along optimal trajectories of stabilization and precise positioning of marine vehicle, under conditions of environment uncertainty and taking into account functional limitations, requires improvement and practical implementation of robust-optimal control`s principles, which provide solution for relevant functional tasks in real time mode [1].

Development of fundamental control principle with feedback loops [2], [3] is based on wide usage for optimal control`s synthesis: static feedbacks [4], $H_\infty$-synthesis [5] and linear matrix inequalities taking into account effect of random limited disturbances but applied mainly to linear or equivalent linear models of controlled systems including, for example, marine vehicles [6].

Marine vehicles operate at the interface between disturbed air and liquid environments and are described by multidimensional nonlinear stochastic differential systems of equations. Generally, applicable simplifications for control of marine vehicles during functional tasks include: stationarity of external random disturbances, horizontal plane of dynamic oscillations of the object and the number of other assumptions [7]. Marine vehicle is controlled under conditions of insufficient a priori information of vehicle`s parameters and under effect of uncontrolled random external disturbances (irregular sea waves, wind pulsations) and parametric noise caused by pitching. Requirements for maximum speed and accuracy of marine vehicle`s control are determined by navigational safety and conditions under which technological process are carried out.

## II. PROBLEM REVIEW

The problem of vehicles stabilization in operating mode or during movement along predetermined trajectories involves creation of optimal, efficient and physically realizable control systems. One of the most efficient systems in term of time or energy consumption are optimal control systems with variable structure [8] – [10].

During marine vehicle functioning, an uncontrolled impact of external extreme disturbances caused by sea current, wind and irregular sea waves, as well as incomplete certainty of the parameters of a mathematical model of a marine vehicle (attached masses, resistance coefficients, etc.) takes place. To reduce these influences, robust control systems can be used to ensure sufficient invariance to the uncertainty of marine vehicle's model and the environment. At the same time, the process of synthesis of robust control is significantly complicated by the nonlinearity of the object's model and requires the creation of sensitive algorithms that can stabilize a marine vehicle with minimal deviations from the optimal trajectory with condition for the error vector $\mathbf{E}(t)$

$$\ddot{\mathbf{E}}(t)+\mathbf{G}_1\dot{\mathbf{E}}(t)+\mathbf{G}_2\mathbf{E}(t)=0, \qquad (1)$$

$\mathbf{G}_1$, $\mathbf{G}_2$ is the positively defined symmetric weight matrices.

Thus, the purpose of the article is to synthesize robust control system for nonlinear model of marine vehicle during stabilization processes under conditions of uncertainty.

## III. PROBLEM SOLUTION

In the most generalized form, dynamics of a marine vehicle during maneuvering and dynamic positioning, taking into account generally accepted assumptions about oscillations in horizontal plane, can be represented in the vector-matrix form [7], [8]

$$\dot{\mathbf{X}}(t)=\mathbf{A}(\mathbf{X})\mathbf{X}(t)+\mathbf{B}\mathbf{U}(t)+\mathbf{C}\mathbf{F}(t), \qquad (2)$$

where $\mathbf{X}(t)$ is the state coordinates vector; $\mathbf{U}(t)$ is the vector of control forces and moment; $\mathbf{F}(t)$ is the vector of forces and moment of external disturbances; $\mathbf{A}(\mathbf{X})$, $\mathbf{B}$, $\mathbf{C}$ are matrices of state coordinates, inertial and aerohydrodynamic coefficients.

Trajectories, with the given boundary conditions and restrictions on control actions, will be optimal (2) when object moves with maximum possible number of maximum possible values of state coordinates vector's derivatives

$$\max_{k}\max_{\overset{(k)}{\mathbf{X}}(t_0)}\left\{\dot{\mathbf{X}}[\overset{(k)}{\mathbf{X}}(t_0),t]\right\}$$

The transition of dynamic object from the initial segment to a predefined segment of the trajectory and taking into account the requirements of physical feasibility of control is described by the following equations

$$\mathbf{X}(t_i^s)=\mathbf{X}(t_{i-1}^s)+\ldots\pm\overset{(m)}{\mathbf{X}}(t_{i-1}^s)\frac{(t_i^s-t_{i-1}^s)^m}{m!},$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots,$$

$$\overset{(m-1)}{\mathbf{X}}(t_i^s)=\overset{(m-1)}{\mathbf{X}}(t_{i-1}^s)\pm\overset{(m)}{\mathbf{X}}(t_{i-1}^s)(t_i^s-t_{i-1}^s), \qquad (3)$$

where $\mathbf{X}(t_i^s)$ are coordinates vector of marine vehicle; $t_i^s$ is the switching moments of control on *i*th segment of trajectory; $m \le m_{\text{lim}}$ is the system order limited by the physical feasibility of control action.

Constraints of control action restricts the number of possible derivatives of the controlled coordinates. That restriction affects the form of optimal trajectory and significantly complicates its calculation.

For the prescribed boundary conditions and derivatives' values of the object's coordinate vector, taking into account constraints on control actions, and based on the solution of algebraic equations' system (2), algorithm for determination of the sequence of switching moments in feedback loops was developed [8], [9]. This algorithm includes for a multidimensional system introduction of leading, sub leading and driven coordinates [10].

It`s assumed that measurable wind impact is compensated by the relevant control channel, and the compensation of immeasurable marine influence will be considered further during synthesis of robust control channel.

To form control functions, we will use equations of forces (moments) balance for third derivative of state coordinates for nonlinear stationary model of marine vehicles (2) in the form

$$\dddot{\mathbf{X}}(t)=\mathbf{A}(\mathbf{X})\ddot{\mathbf{X}}(t)+2\dot{\mathbf{A}}(\mathbf{X})\dot{\mathbf{X}}(t)$$
$$+\ddot{\mathbf{A}}(\mathbf{X})\mathbf{X}(t)+\mathbf{B}(\mathbf{X})\ddot{\mathbf{U}}(t). \qquad (4)$$

The vector-matrix transformations of system (4) (the argument $\mathbf{X}$ for matrices $\mathbf{A}$ is omitted) create the expressions for control actions

$$\mathbf{B}\ddot{\mathbf{U}}(t)+\mathbf{A}\mathbf{B}\dot{\mathbf{U}}(t)+(\mathbf{A}^2+2\dot{\mathbf{A}}\mathbf{B})\mathbf{U}(t)$$
$$=-[\mathbf{A}^2+2\dot{\mathbf{A}}\mathbf{A}+\mathbf{A}\dot{\mathbf{A}}+\ddot{\mathbf{A}}]\mathbf{X}(t). \qquad (5)$$

Thus, equations (5) form the control for motion along the optimal trajectories (3).

Solution for robust control problem of marine vehicles under conditions of uncertainty, and taking into account controlled external disturbances, is based on use of system with variable structure, which forms reference optimal model for the motion of the linear object [8]. Control signal from the reference model $\mathbf{U}_m$ goes to the input of physical marine vehicle, and then correction signal $\mathbf{U}_c$ is generated in the circuit of robust control by comparing and multiplying the output signal from the reference model with output of the physical object.

Taking into account robust circuit, differential equation (2) takes the form

$$\dot{\mathbf{X}}(t)=\mathbf{A}(\mathbf{X})\mathbf{X}(t)+\mathbf{B}[\mathbf{U}_m(t)+\mathbf{U}_{\tilde{n}}(t)]+\mathbf{C}\mathbf{F}(t). \qquad (6)$$

For reference optimal model equation (1) will take form

$$\dot{\mathbf{X}}_m(t)=\mathbf{A}(\mathbf{X}_m)\mathbf{X}_m(t)+\mathbf{B}\mathbf{U}_m(t)+\mathbf{C}\mathbf{F}(t). \qquad (7)$$

To determine correction signal based on the nonlinear equations (6), (7) an approximate expression for the deviation vector $\mathbf{E}(t)$ is written down as

$$\dot{\mathbf{E}}(t)\approx\mathbf{A}(\mathbf{X}_m)\mathbf{X}_m(t)-\mathbf{A}(\mathbf{X})\mathbf{X}(t)-\mathbf{B}\mathbf{U}_{\tilde{n}}(t). \qquad (8)$$

Equation (8) together with condition for the error vector (1) and the correction signal takes the form for zero initial value $\mathbf{U}_c(0)$

$$\dot{\mathbf{U}}_{\tilde{n}}=\mathbf{B}^{-1}\{-\mathbf{G}_1\mathbf{B}\mathbf{U}_{\tilde{n}}+[\dot{\mathbf{A}}(\mathbf{X}_m)+\mathbf{G}_1\mathbf{A}(\mathbf{X}_m)]\mathbf{X}_m$$
$$-\mathbf{A}(\mathbf{X}_m)\dot{\mathbf{X}}_m-[\dot{\mathbf{A}}(\mathbf{X})+\mathbf{G}_1\mathbf{A}(\mathbf{X})]\mathbf{X}-\mathbf{A}(\mathbf{X})\dot{\mathbf{X}}+\mathbf{G}_2\mathbf{E}\}.$$

On the structure scheme Fig. 1, a detailed explanation of how the correction signal, generated by robust control system, together with the optimal system are used to control marine vehicle.

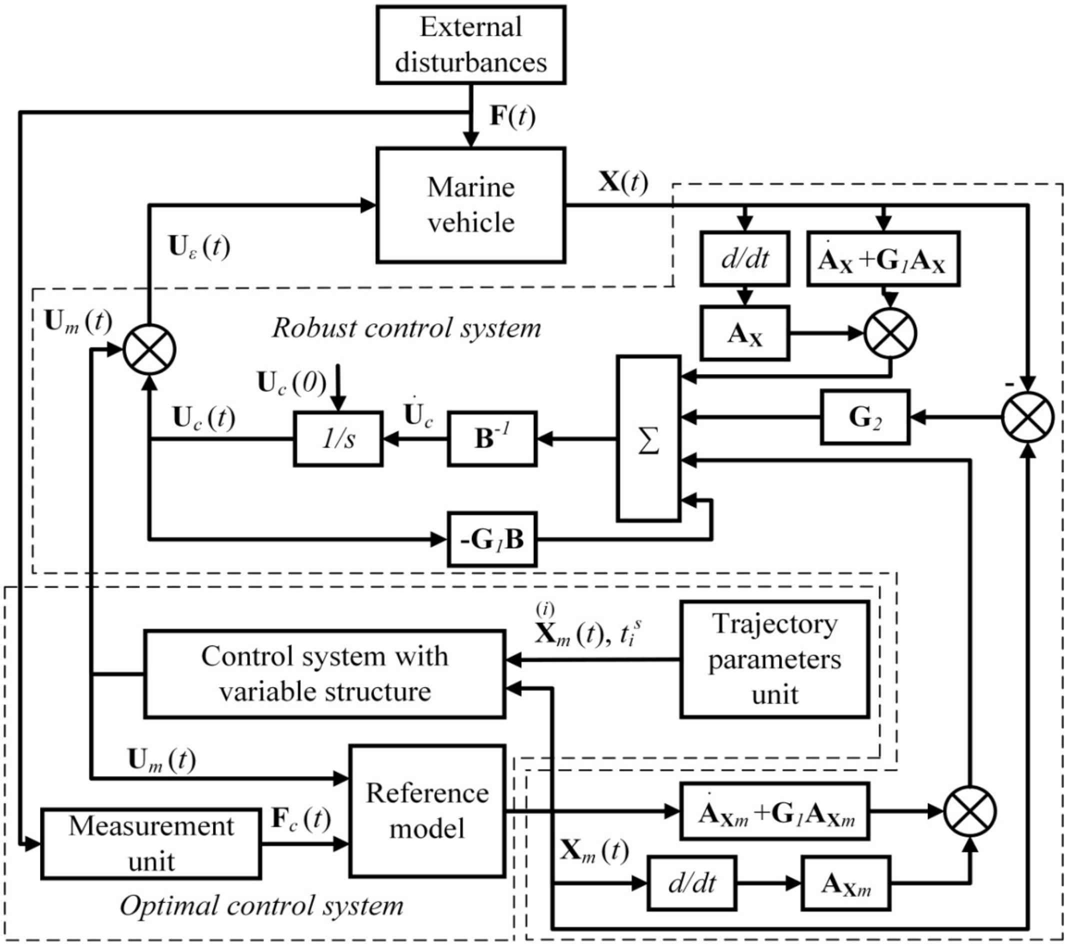

Fig. 1. Structure scheme

## IV. SIMULATION RESULTS OF SHIP'S MANEUVERING

Uncontrolled external disturbances in the form of irregular sea waves were generated by the forming filter. Parametric noise in the measurement of output coordinates was generated by Gaussian white noise with relevant intensity. The uncertainty of physical marine vehicle's parameters relatively to its mathematical model was set as ± 15% nominal values. Simulation of the stabilization process of the marine vehicle shows for the robust-optimal control system the following characteristics: angle of rudder over time $\alpha(t)$ – Fig. 2, angular velocity over course angle $\omega(\psi)$ – Fig. 3, angular velocity over time $\omega(t)$ – Fig. 4 and errors of course angle over time $\varepsilon_\psi(t)$ – Fig. 5, providing accuracy of the control process with errors less than 3%.

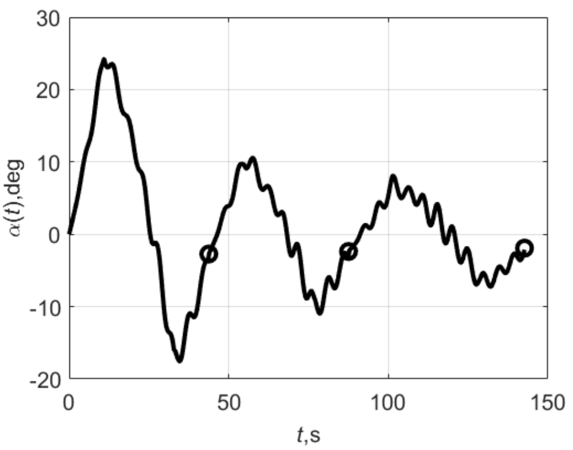

Fig. 2. Angle of rudder over time

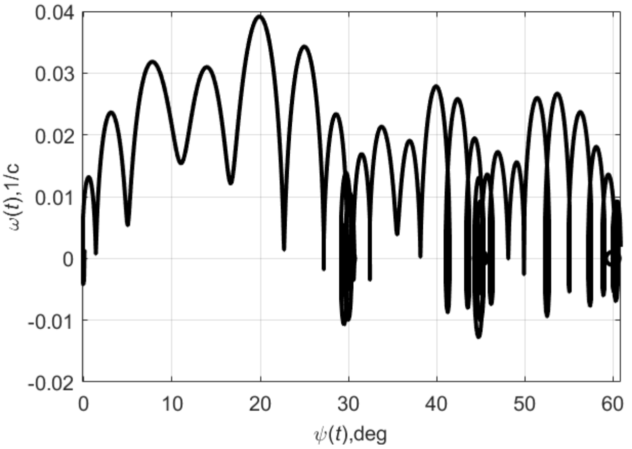

Fig. 3. Angular velocity over course angle

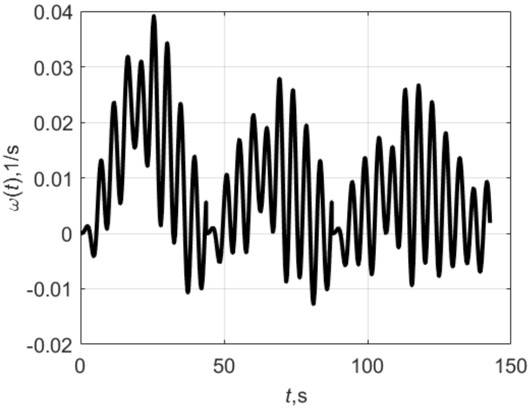

Fig. 4. Anglar velocity over time

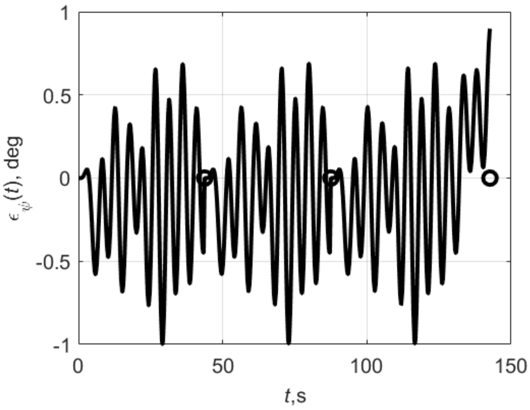

Fig. 5. Errors of course angle over time

## V. CONCLUSION

Based on system with variable structure and taking into account criterion of optimality for the maximum operating speed, robust control system for nonlinear model of marine vehicles has been developed. Nonlinear approach to synthesize robust control based on determination of weigh matrices is practically applicable for a wide class of mobile objects and for various technical tasks.

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**В. Л. Тимченко, Д. О. Лебедєв. Нелінійна робастна система керування для стабілізації морського об'єкта**

Розглянуто нелінійну робастну систему керування, яка покращує процес керування морським рухомим об'єктом за умови невизначеності морського рухомого об'єкта та навколишнього середовища. Нелінійна робастна система дозволяє зберігати задану оптимальну стабілізаційну траєкторію нелінійного морського рухомого об'єкта на місцевості, створюючи додатковий робастний контур, що дозволяє компенсувати різні типи невизначеності. Оптимальна система швидкодії на основі змінної структури використовується для визначення оптимальної траєкторії стабілізації з урахуванням заданої величини моделі морського об'єкта, необхідного типу траєкторій стабілізації та обмежень на керуючі дії. Нелінійна робастна система вирішує завдання керування нелінійними морськими об'єктами під час маневрування та динамічного позиціонування в умовах невизначеності.

**Ключові слова:** морський об'єкт; робастне керування; нелінійна система керування; змінна структура.

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**В. Л. Тимченко, Д. О. Лебедев. Нелинейная робастные система управления для стабилизации морского объекта**

Рассмотрена нелинейная робастная система управления, которая улучшает процесс управления морским транспортным средством при неопределенности морского транспортного средства и окружающей среды. Нелинейная робастная система позволяет сохранять заданную оптимальную стабилизационную траекторию нелинейного морского транспортного средства в нужной местности, создавая дополнительный робастный контур, который позволяет компенсировать различные типы неопределенности. Оптимальная система быстродействия на основе переменной структуры используется для определения оптимальной траектории стабилизации с учетом заданной величины модели морского объекта, необходимого типа траекторий стабилизации и ограничений на управляющие действия. Нелинейная робастная система решает задачи управления нелинейными морскими объектами во время маневрирования и динамического позиционирования в условиях неопределенности.

**Ключевые слова:** морской объект; робастное управление; нелинейная система управления; переменная структура.

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