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[1]A. K. Ablesimov,
[2]T. P. Zhmurchyk,
[3]A. A. Rud,
[4]A. O. Tsoba

DIGITAL STABILIZATION SYSTEM

[1,2]Aviation Computer-Integrated Complexes Department, National Aviation University, Kyiv, Ukraine
E-mails: [1]alexander.ablesimov@gmail.com, [2]tanichka.zm@gmail.com,
[3]forwt19i@gmail.com, [4]arttsioba@gmail.com

Abstract**—***A model of a discrete system for stabilizing the ship's course has been developed and the results of research on the choice of an optimal digital controller for it are presented. The method of the describing function is used as a research method. In developing a mathematical model of a discrete system, a typical block diagram of a continuous stabilization system was used. The location of the quantizer and extrapolator in it was determined. The latter was selected as a zero-order extrapolator, as the simplest, easily implemented with standard equipment, although the use of a first-order extrapolator can give some advantage in the accuracy of information recovery. Modeling is carried out in state variables and in a classical way based on a discrete transfer function of stabilization system. For the research, the package of visual block simulation modeling of the MatLab matrix system was used. Modeling of the system of stabilization with different types of controllers allowed to carry out their comparative assessment. To improve the properties of the digital proportional integral derivative controller, it is proposed to introduce in it a correction system.*

Index Terms—Ship; stabilization system; course; Z-transformation; quantizer; extrapolator; controller; correction; discrete transfer function.

I. INTRODUCTION

Stabilization systems are special automatic control systems designed to guide and maintain a given spatial position of the control object when its base oscillates.

Despite the fact that stabilization systems differ significantly in design, they are performed according to the same functional schemes. However, the control processes occurring in stabilization systems are described by similar linear differential equations. As a result, their block diagrams are identical, which allows to obtain a typical (Fig. 1) block diagram of a continuous stabilization system.

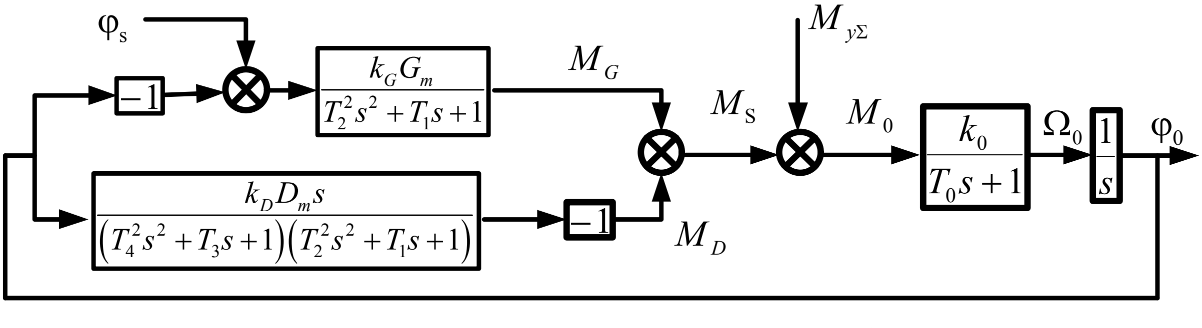


Fig. 1. Typical block diagram of a continuous stabilization system: $G_m = k_{\mathrm{ds}} k_{\mathrm{reg}}$ is the structural stiffness of the system; $D_m = k_{\mathrm{sds}} k_{\mathrm{reg}}$ is the constructive damping of the system; k_{ds} is the transfer coefficient of the deviation sensor of the control object; k_{sds} is the transfer coefficient of the sensor of the speed of deviations of the control object; k_G, k_D are stiffness and damping adjustment coefficients; k_{reg} is the transfer coefficient of the regulator

The moment of stabilization M_{S} is formed on the channels of the sensor of angular deviation and the sensor of speed of angular deviation of the control object:

$$\overline{M}_{\mathrm{S}} = \overline{M}_G + \overline{M}_D \equiv k_G G_m + k_D D_m .$$

The presence of a block diagram – a linear model, of a continuous stabilization system allows you to perform its analysis and synthesis in the design or upgrade.

We are currently witnessing the widespread use of discrete (digital) automatic systems in technology. A linear discrete automatic control system is a system that, in addition to the links described by linear differential equations, contains an element of discrete action that converts a continuous input effect into a certain sequence of pulses. The discrete element can be a stand-alone functional device or be part of analog-to-digital converters included in the control system with digital control devices.

Discrete elements and digital computing devices are introduced into automatic control systems in cases where the tasks require complex information processing or performing such operations that can not be performed with the required accuracy using analog devices.

During the conversion by a discrete element of a continuous signal into a discrete one, it performs two operations: quantization of the signal and its pulse modulation. In systems with digital controllers, the discrete element is also responsible for the function of translating the discrete signal into binary code.

II. PROBLEM STATEMENT

The problems of analysis and synthesis of discrete (digital) automatic systems are much more complex than similar problems for linear continuous systems. For example, the stability of discrete systems in contrast to analog linear ones is determined in a limited range of frequencies of disturbing influences, and the nature of their transient process may, depending on the system parameters, end in a finite number of steps. All this requires the use of special methods of analysis and synthesis of discrete systems.

In this regard, it is of some interest the development of a discrete stabilization system, such as the course of the ship, with an optimal digital controller that meets modern requirements for quality and safety of navigation of seagoing vessels.

III. PROBLEM SOLUTION

The most common methods of describing discrete systems are methods based on the application of differences of lattice functions and Z-images of difference equations of their motion. This makes it possible to move to structural images of the equations of discrete systems with subsequent modeling of systems, their analysis and synthesis, for example, in the MatLab environment.

To build a mathematical model – a structural scheme, a discrete system of stabilization of the ship's course, we use a typical structural scheme of a continuous stabilization system. Considering the time constants T_4, T_3 of the sensor of the angular velocity of the ship's deviation from the course as the values of the second order of smallness, we obtain the calculated block diagram of a continuous system of stabilization of the ship's course. The scheme is shown in Fig. 2.

Determine the location of the quantizer in model and the type of extrapolator. In the general case, there are three options, which are shown in Fig. 3.

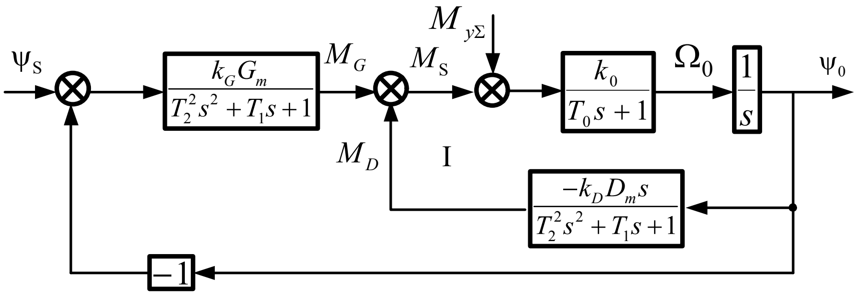
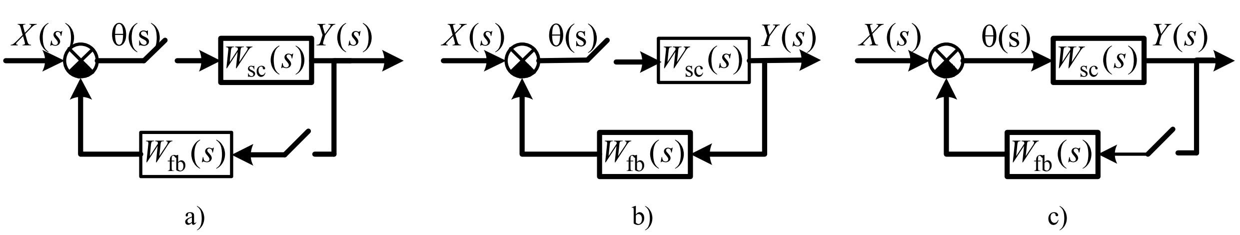


Fig. 2. Block diagram of a continuous system of stabilization of the ship's course



a) b) c)

Fig. 3. Quantizer location options

In the first and second cases, the equivalent discrete transfer functions of the system are determined by algorithms

$$W_a[z] = \frac{W_{sc}[z]}{1 + W_{sc}[z] W_{fb}[z]}, \quad W_b[z] = \frac{W_{sc}[z]}{1 + \overline{W_{sc} W_{fb}}[z]}.$$

In the third – for an equivalent discrete transfer function we will accept

$$W_{\text{c}}[z]=\frac{1}{1+\overline{W_{\text{sc}}W_{\text{fb}}}[z]},$$

provided that the input signal is a signal $X(s)W_{\text{sc}}(s)$.

In order to reduce information loss in the system, immediately after the operation of quantization of the continuous signal a data recovery operation is introduced. It is implemented by using an extrapolator.

There are zero and first order extrapolators. Their transfer functions are accordingly equal

$$W_{\text{e0}}(s)=\frac{1-e^{-Ts}}{s},\quad W_{\text{e1}}(s)=\left(\frac{1-e^{-Ts}}{s}\right)^2\cdot\left(\frac{Ts+1}{T}\right).$$

In practice, the use of a first-order extrapolator can give some gain in the accuracy of information recovery with frequent quantization of fairly smooth signals. The vast majority of real recovery devices are described by the model of the zero-order extrapolator. This is the simplest extrapolator, easily implemented by using standard equipment.

The discrete transfer function of the series connection of the quantizer, the zero-order extrapolator and the subsequent dynamic link $W(s)$ can be found as

$$W[z]=\frac{z-1}{z}Z\left\{\frac{W(s)}{s}\right\}.$$

Assuming the transfer functions of the straight chain $W_{\text{sc}}(s)$ and the feedback chain $W_{\text{fb}}(s)$ are equal

$$W_{\text{sc}}(s)=\frac{1}{s+1},\qquad W_{\text{fb}}(s)=\frac{1}{s+1},$$

and zero-order extrapolators, transient characteristics were obtained for each of the three systems shown in Fig. 3. The results of calculations are shown in Fig. 4.

Analysis of the graphs shows that wherever the quantizer and extrapolator are located, the transient characteristics of the system do not differ from each other. Therefore, for further research, was chosen a variant of Fig. 3b of their location.

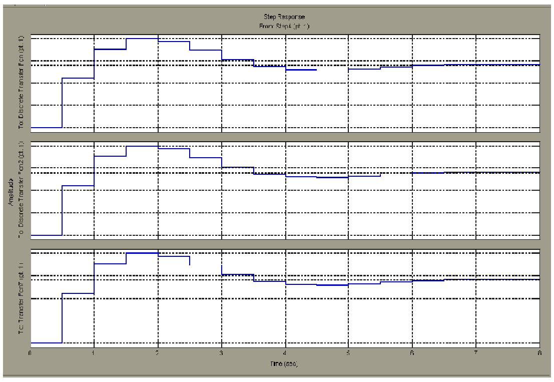


Fig. 4. Transients of the system with different options of the placement of the quantizer with extrapolator

Based on the above, the block diagram of a discrete stabilization system after convolution of the circuit I takes the form shown in Fig. 5.

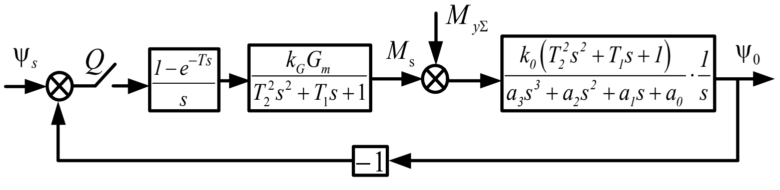
Guided by the principle of superpositions, mathematical models of the stabilization system for each of the channels of influence on the control object were reduced to the form in Fig. 6.

Due to the limitations of the scope of work, further studies of the system on the control signal channel will be presented. The method of assessing the impact of disturbing influences is similar.

The presence of the structural scheme of the system allows to calculate its discrete transfer functions: $W_{\text{eq}}[z]$ is the equivalent and $W_{\text{oc}}[z]$ is the open circuit. To do this, simply perform a Z-transformation.

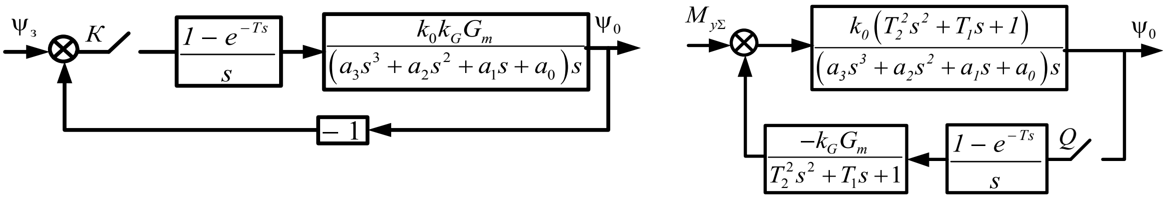
$$W_{\text{eq}}[z]=\frac{z-1}{z}\cdot Z\left\{\frac{k_0k_GG_m}{a_3s^4+a_2s^3+a_1s^2+a_0s+k_0k_GG_m}\cdot\frac{1}{s}\right\},$$

$$W_{\text{oc}}[z]=\frac{z-1}{z}Z\left\{\frac{k_0k_GG_m}{a_3s^4+a_2s^3+a_1s^2+a_0s}\cdot\frac{1}{s}\right\}.$$



$$a_3=T_2^2T_0,\ a_2=\left(T_2^2+T_1T_0\right),\ a_1=\left(T_1+T_0\right),\ a_0=\left(1+k_0k_DD_m\right)$$

Fig. 5. Block diagram of a discrete stabilization system



a) b)

Fig. 6. Mathematical models of the system: (a) by the control signal channel; (b) by the disturbing influences channel

In the work for the decision of the given problem the author used a package of visual block simulation modeling of matrix system MatLab. Taking into account the values of the system parameters according to [1] – [4], we determine the equivalent discrete transfer function by the control signal

$$\text{Wz} = \frac{0.0001579\ z\text{^}2 + 0.0006654\ z + 0.0002192}{z\text{^}4 - 1.713\ z\text{^}3 + 0.6966\ z\text{^}2 + 0.01068\ z + 0.006738}\ .$$

Modeling of the stabilization system was performed on this function. Figure 7 shows a discrete model in state variables.

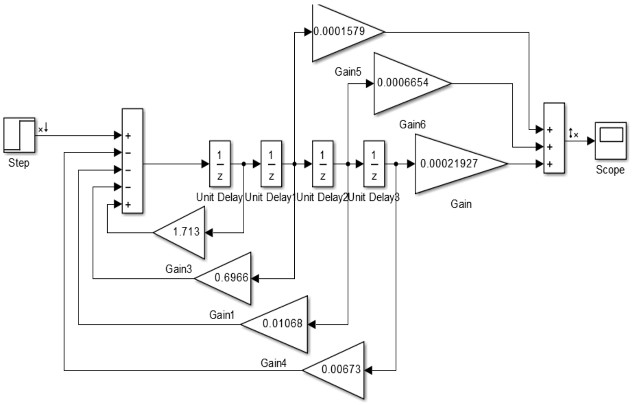


Fig. 7. Model in state variables

Figure 8 shows a classical model be using a discrete transfer function.

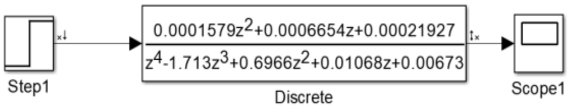


Fig. 8. Classic model

The models give the same results. Their using is based on the tasks solved by the researcher. The sampling period of the signal was taken to be $T = 0.5$ s. Models of an open loop of the stabilization system were obtained in a similar way.

The results of research using the developed models are presented in Figs 9 and 10.

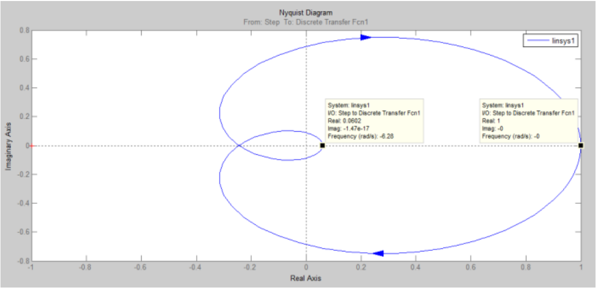
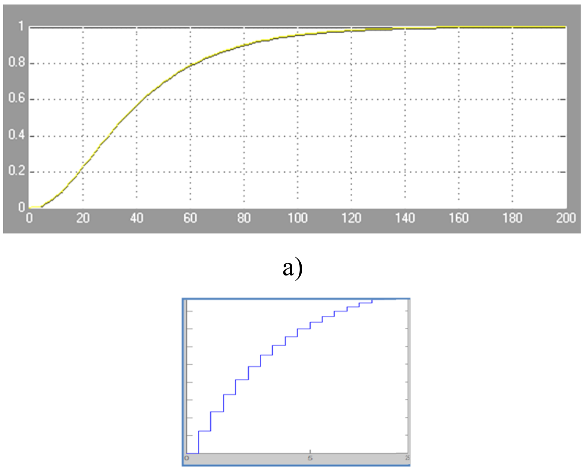


Fig. 9. Amplitude-phase frequency response of a discrete open-loop stabilization system



a)

b)

Fig. 10. Transient response (a) and its fragment (b) of discrete stabilization system

Thus, according to the analogue of the Nyquist criterion (Fig. 9), with the selected parameters of the controller, the discrete stabilization system will be stable and, therefore, efficient. This conclusion is confirmed by the response of the system (Fig. 10) to the step control action.

Circuit solutions of digital controllers of stabilization systems can be different. Proportional-integro-differentiating (PID), proportional-integrating (PI), proportional-differentiating (PD) regulators deserve attention.

In Fig. 11 shows a block diagram of a stabilization system with a digital PID - controller.

Transfer function of the PID-controller:

$$W_{\mathrm{PID}}[z] = k_{\mathrm{reg}} + \frac{k_{\mathrm{d}}(z-1)}{T_{\mathrm{d}}z} + \frac{k_{\mathrm{i}}T_{\mathrm{i}}z}{z-1}.$$

It contains three components: proportional, differentiating and integrating. The advantage of the regulator is a quick system response to the mode, an accurate content of a given initial value and a quick response on control influences.

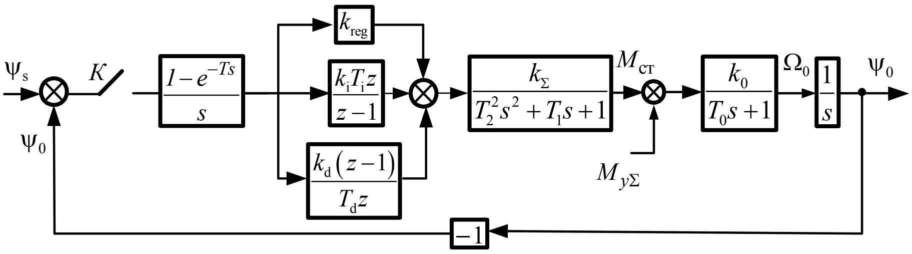


Fig. 11. Block diagram of the stabilization system with a digital PID-controller

Models of the system with PD- and PI-controllers were obtained by imposing restrictions on the PID - model.

PD-controller consists of parallel connected proportional and differentiating links

$$W_{\mathrm{PD}}[z] = k_{\mathrm{reg}} + \frac{k_{\mathrm{d}}(z-1)}{T_{\mathrm{d}}z}.$$

It responds to both the mismatch signal $(\psi_s - \psi_0)$ and the rate of change. Due to this, when using the PD-control law, the effect of advanced control is achieved.

The PI-controller is a proportional controller with an integral component. The latter is required to eliminate the static error of the system, which is characteristic of the proportional controller. The transfer function of the PI-controller has the form

$$W_{\mathrm{PI}}[z] = k_{\mathrm{reg}} + \frac{k_{\mathrm{i}}T_{\mathrm{i}}z}{z-1}.$$

Simulation in the MatLab environment of the ship course stabilization system with various types of digital controllers made it possible to carry out a comparative assessment of the controllers and choose the best one.

Close to the optimal, based on the basic requirements for quality indicators of marine control systems, was a digital PID- controller. The transient characteristic (curve 1) of the stabilization system of the course of the ship with the industrial PID-controller is given in Fig. 12.

The disadvantages of using an industrial digital PID-controller include the presence, albeit small, but over-regulation of the transient process, which is extremely unacceptable for control objects of high inertia. Therefore, in order to increase the efficiency of the discrete stabilization system in the work, it is proposed to introduce a correction system in the industrial digital controller (Fig. 13).

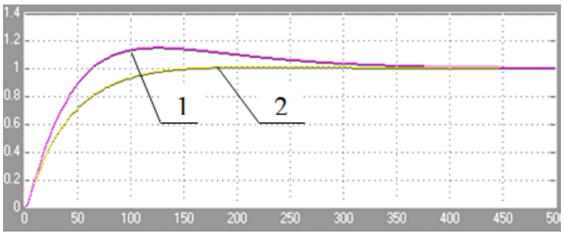


Fig. 12. Transient functions of the system: 1 is the industrial PID-controller; 2 is the PID-controller with correction

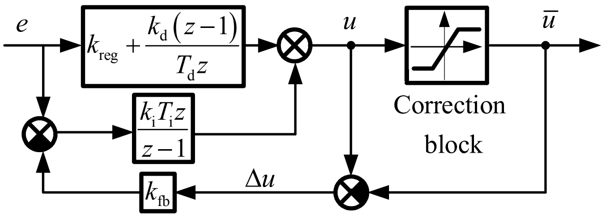


Fig. 13. Digital PID-controller with correction system

The use of the proposed correction unit is justified by the fact that in ship control systems there are restrictions on the maximum value of the control effect.

The principle of operation of the correction system is quite fully described in the work of the authors [2].

The transient characteristic (curve 2) of the stabilization system with an upgraded digital PID-controller is shown in Fig. 13.

Comparison (Fig. 13) of the dynamics of the stabilization systems with different types of PID-controllers shows that both systems of course have the same constant value, their speed meets the established requirements, but in system 2 the process proceeds without over-regulation.

Summarizing the results of research, we note that for a discrete (digital) course stabilization system from the point of view of the quality of control processes is optimal digital PID-controller with the proposed correction system.

IV CONCLUSIONS

A feature of discrete (digital) control systems is the possibility of complex information processing and operations that cannot be performed with the required accuracy using analog devices.

The developed mathematical model of the discrete stabilization system of the ship's course allowed to synthesize a digital controller in order to provide the necessary indicators of the quality of the system.

Theoretical and experimental studies have shown good convergence of results.

The synthesis of digital PID-controllers allowed to choose the optimal one. Thus, for a discrete stabilization system, the ship's course is a digital PID-controller with the proposed correction system.

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Ablesimov Aleksandr. Candidate of Science (Engineering). Professor.
Aviation Computer Integrated Complexes Department, National Aviation University, Kyiv, Ukraine.
Education: Military Academy of Armored Forces, Moscow, USSR, (1971).
Research interests: Automatic control systems.
Publications: 296.
E-mail: alexander.ablesimov@gmail.com

Zhmurchyk Tatyana. Student.
Aviation Computer-Integrated Complexes Department, National Aviation University, Kyiv, Ukraine.
Research interests: Automatic control systems.
Publications: 3.
E-mail: tanichka.zm@gmail.com

Rud Andrei. Student.
Aviation Computer-Integrated Complexes Department, National Aviation University, Kyiv, Ukraine.
Research interests: Automatic control systems.
Publications: 1.
E-mail: forwt19i@gmail.com

Tsoba Arthur. Student.
Aviation Computer-Integrated Complexes Department, National Aviation University, Kyiv, Ukraine.
Research interests: Automatic control systems.
Publications: 1.
E-mail: arttsioba@gmail.com

О. К. Аблесімов, Т. П. Жмурчик, А. А. Рудь, А. О. Цьоба. Цифрова система стабілізації

Розроблено модель дискретної системи стабілізації курсу корабля та представлено результати досліджень щодо вибору оптимального цифрового регулятора до неї. Як метод дослідження використовується метод описуваної функції. При розробці математичної моделі дискретної системи використано типову блок-схему системи безперервної стабілізації. Визначено місце розташування в системі квантувача та екстраполятора. У якості останнього обрано екстраполятор нульового порядку, як найпростіший, що легко реалізується на стандартному обладнанні, хоча використання екстраполятора першого порядку може давати певну перевагу в точності відновлення інформації. Моделювання проводилося в змінних стану і класичним способом на основі дискретної передатної функції системи стабілізації. Для дослідження використовувався пакет візуального імітаційного блочного моделювання матричної системи MatLab. Моделювання системи стабілізації з різними типами регуляторів дозволило провести їх порівняльне оцінювання. Для поліпшення властивостей цифрового ПІД-регулятора пропонується ввести в нього систему корекції.

Ключові слова: корабель; система стабілізації; курс; Z-перетворення; квантувач; екстраполятор; регулятор; корекція; дискретна передатна функція.

Аблесімов Олександр Костянтинович. Кандидат технічних наук. Професор.
Кафедра авіаційних комп’ютерно-інтегрированних комплексів, Національный авіаційний університет, Київ, Україна.
Освіта: Військова академія бронетанкових військ, Москва, СРСР, (1971).
Направлення наукової діяльності: системи автоматичного керування.
Кількість публікацій: 296.
E-mail: alexander.ablesimov@gmail.com

Жмурчик Тетяна Петрівна. Студентка.
Кафедра авіаційних комп’ютерно-інтегрованих комплексів, Національний авіаційний університет, Київ, Україна.
Напрям наукової діяльності: системи автоматичного керування.
Кількість публікацій: 3.
E-mail: tanichka.zm@gmail.com

Рудь Андрій Андрійович. Студент.
Кафедра авіаційних комп’ютерно-інтегрованих комплексів, Національний авіаційний університет, Київ, Україна.
Напрям наукової діяльності: системи автоматичного керування.
Кількість публікацій: 1.
E-mail: forwt19i@gmail.com

Цьоба Артур Олександрович. Студент.
Кафедра авіаційних комп’ютерно-інтегрованих комплексів, Національний авіаційний університет, Київ, Україна.
Напрям наукової діяльності: системи автоматичного керування.
Кількість публікацій:1.
E-mail: arttsioba@gmail.com

А. К. Аблесимов, Т. П. Жмурчик, А. А. Рудь, А. А. Цьоба. Цифровая система стабилизации

Разработана модель дискретной системы стабилизации курса корабля и представлены результаты исследований по выбору оптимального цифрового регулятора для нее. Как метод исследования используется метод описываемой функции. При разработке математической модели дискретной системы была использована типовая блок-схема системы непрерывной стабилизации. Определено место расположения в ней квантователя и экстраполятора. В качестве последнего был выбран экстраполятор нулевого порядка, как самый простой, легко реализуемый на стандартном оборудовании, хотя использование экстраполятора первого порядка может давать определенное преимущество в точности восстановления информации. Моделирование проводилось в переменных состояния и классическим способом на основе дискретной передаточной функции системы стабилизации. Для исследования был использован пакет визуального имитационного блочного моделирования матричной системы MatLab. Моделирование системы стабилизации с различными типами регуляторов позволило провести их сравнительную оценку. Для улучшения свойств цифрового ПИД-регулятора предлагается ввести в него систему коррекции.

Ключевые слова: корабль; система стабилизации; курс; Z-преобразование; квантователь; экстраполятор; регулятор; коррекция; дискретная передаточная функция.

Аблесимов Александр Константинович. Кандидат технических наук. Профессор.
Кафедра авиационных компьютерно-интегрированных комплексов, Национальный авиационный университет, Киев, Украина.
Образование: Военная академия бронетанковых войск, Москва, СССР (1971).
Направление научной деятельности: системы автоматического управления.
Количество публикаций: 296.
E-mail: alexander.ablesimov@gmail.com

Жмурчик Татьяна Петровна. Студентка.
Кафедра авиационных компьютерно-интегрированных комплексов, Национальный авиационный университет, Киев, Украина.
Направление научной деятельности: системы автоматического управления.
Количество публикаций: 3.
E-mail: tanichka.zm@gmail.com

Рудь Андрей Андреевич. Студент.
Кафедра авиационных компьютерно-интегрированных комплексов, Национальный авиационный университет, Киев, Украина.
Направление научной деятельности: системы автоматического управления.
Количество публикаций: 1.
E-mail: forwt19i@gmail.com

Цьоба Артур Александрович. Студент.
Кафедра авиационных компьютерно-интегрированных комплексов, Национальный авиационный университет, Киев, Украина.
Направление научной деятельности: системы автоматического управления.
Количество публикаций: 1.
E-mail: arttsioba@gmail.com