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DESIGN OF ROBUST NAVIGATION AND STABILIZATION LOOPS OF PRECISION ATTITUDE AND HEADING REFERENCE SYSTEM

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Abstract

Purpose: *The paper focuses on problems of design of robust precision attitude and heading reference systems, which can be applied in navigation of marine vehicles. The main goal is to create the optimization procedures for design of navigation and stabilization loops of the multimode gimballed system. The optimization procedure of the navigation loop design is based on the parametric robust H_2/H_∞-optimization. The optimization procedure of the stabilization loop design is based on the robust structural H_∞-synthesis.* ***Methods:*** *To solve the given problem the methods of the robust control system theory and optimization methods are used.* ***Results:*** *The kinematical scheme of the precision gimballed attitude and heading reference system is represented. The parametrical optimization algorithm taking into consideration features of the researched system is given. Method of the mixed sensitivity relative to the researched system design is analyzed. Coefficients of the control laws of navigation loops are obtained based on optimization procedure providing compromise between accuracy and robustness. The robust controller of the stabilization loop was developed based on robust structural synthesis using method of the mixed sensitivity. Simulation of navigation and stabilization processes is carried out.* ***Conclusions:*** *The represented results prove efficiency of the proposed procedures, which can be useful for design of precision navigation systems of the moving vehicles.*

Keywords*:* attitude and heading reference system; method of the mixed sensitivity; precision navigation; robust parametrical optimization; robust structural synthesis.

1. Introduction

Operation of precision attitude and heading reference systems is implemented in conditions of uncertainties caused by both inaccuracies of the mathematical description of the real system and influence of the internal and coordinate disturbance. Mainly, the systems designed for operation at marine vehicles are subjected to influence of the disturbances caused by sea irregular waves. The modern approach to these systems design is creation of the robust systems able to operate in conditions of both the parametrical structured and the external (coordinate) disturbances.

The precision attitude and heading reference systems of marine vehicles must carry out following functions:

1) preliminary stabilization of navigation sensors (accelerometers) in the mode of preliminary alignment in the horizontal plane (preliminary levelling);

2) precision stabilization of navigation sensors (gyroscopes and accelerometers) in the mode of precision alignment in the horizontal plane (precision levelling);

3) initial alignment in the meridian plane;

4) joint stabilization and precision determination of heading in the mode of the gyroscopic compass.

The precision attitude and heading reference system can be designed based on the triaxial gimballed platform (see Fig. 1). Such a system includes two dynamically tuned gyros (DTGs), three accelerometers and servo systems. The gyroscopes carry out functions of the vertical gyroscope and directional gyroscope respectively. Such a combination provides determination of the vehicle attitude and heading.

The scheme represented in Fig. 1 has some features [1]. The axis of the external gimbal of the platform to be stabilized is directed along the vehicle longitudinal axis. Stabilization of the platform is implemented by means of DTGs. In its turn, the gyroscopes are corrected by means of

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accelerometers using the integral correction. The accelerometer mounted at the gimbals vertical axis allows to compensate an error caused by the vertical acceleration and to improve accuracy of alignment in the horizontal plane.

Design of attitude and heading reference system by means of such a scheme provides modelling of the true horizon plane. The system becomes undisturbed by external accelerations. This is important for operation of the system in conditions of sea irregular waves and the marine vehicle manoeuvring.

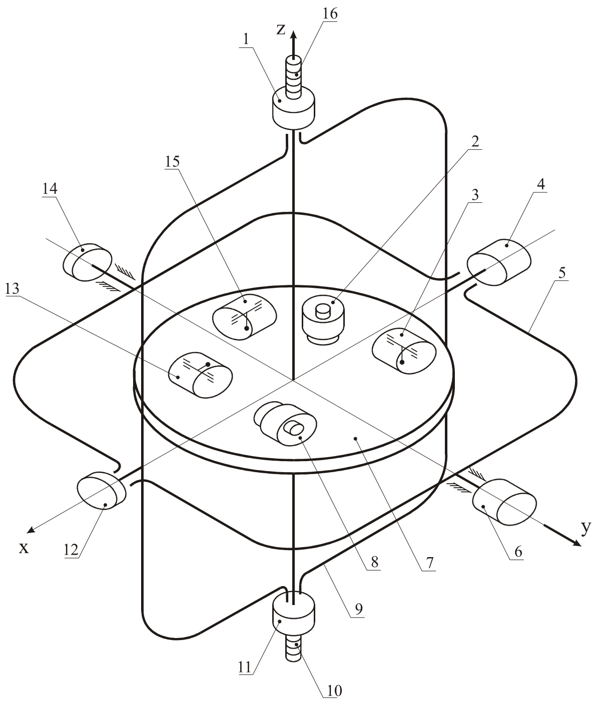


Fig. 1. The scheme o the attitude and heading reference system based on the triaxial gimballed platform: *x*,*y*,*z* are axes of the body-axis reference frame; 1, 12, 14 are angle-data transmitters; 4, 6, 11 are torque sensors; 5, 9 are external and internal gimbals frames; 10, 16 are current contacts; 7 is the platform; 3, 13, 15 are the accelerometers; 2, 8 are DTGs

To design precision attitude and heading reference systems it is necessary to solve two basic problems. In the first place, it is necessary to create navigation laws, which are different for various modes of system operation. In the second place, it is necessary to design stabilization loops. The first problem can be solved by means of robust parametric optimization using great experience on designing of systems of such a class. In this case, the structure of navigation laws is believed to be known. Coefficients of navigation laws can be determined based on robust parametrical optimization. The second problem lies in design of controllers of stabilization loops using the robust structural synthesis.

2. Analysis of the latest researches and publications

Problems of the robust control systems design are considered in many papers, for example, [2]. These achievements can be useful for creation of the design procedures of robust gimballed attitude and heading reference systems. The latter problem has not been studied at the necessary level to nowadays. The newest achievements of design of the inertially stabilized platform and the gimballed inertial navigation systems and areas of their application are given in the papers [3, 4]. The full mathematical description of the researched system necessary for creation of the design procedures is represented in [5].

3. Research tasks

The main goal of this research is to represent design procedures of the robust precision gimballed attitude and reference system including its navigation and stabilization loops. The proposed procedures will be implemented and the design results will be shown in the form of simulation of navigation and stabilization processes.

4. Robust parametrical optimization

To increase efficiency of the robust parametric optimization it is possible using the mixed H_2 / H_∞ approach.

It is convenient to implement robust parametric stabilization using the complex criterion, which takes into consideration performance indices of both accuracy and robustness. Such a criterion can be determined based on H_2-, H_∞-norms of the functions of sensitivity of the closed loop system. Influence of every component is regulated by means of weighting coefficients depending on system features.

For the above mentioned class of systems, the complex criterion must include indices of nominal and disturbed system accuracy. Moreover, the complex criterion must include index of nominal system robustness. Taking into account these considerations, the complex optimization criterion becomes [6, 7]

$$\begin{aligned} J_{H_2/H_\infty} &= J_{H_2}^{d} + J_{H_2}^{s} + J_\infty + PF = \\ &= \lambda_2^{\text{nom d}} \,\|\, \Phi_{S1}(\mathbf{K},\mathbf{x},\mathbf{u},j\omega) \,\|_2^{\text{nom d}} + \\ &+ \lambda_2^{\text{nom s}} \,\|\, \Phi_{S2}(\mathbf{K},\mathbf{x},\mathbf{u},j\omega) \,\|_2^{\text{nom s}} + \\ &+ \lambda_\infty^{\text{nom}} \,\|\, \Phi(\mathbf{K},\mathbf{x},\mathbf{u},j\omega) \,\|_\infty^{\text{nom}} + PF, \end{aligned} \tag{1}$$

here $\| \Phi_{S1}(\mathbf{K},\mathbf{x},\mathbf{u},j\omega) \|_2^{\text{nom d}}$, $\| \Phi_{S2}(\mathbf{K},\mathbf{x},\mathbf{u},j\omega) \|_2^{\text{nom s}}$ are H_2-norms of functions of sensitivity of the nominal system and the system disturbed by the coordinate disturbances (deterministic and stochastic cases); $\| \Phi(\mathbf{K},\mathbf{x},\mathbf{u},j\omega) \|_\infty^{\text{nom}}$ is H_∞-norm of the complementary sensitivity function of the nominal system; $\lambda_2^{\text{nom d}}, \lambda_2^{\text{nom s}}, \lambda_\infty^{\text{nom}}$ are weighting coefficients of the above stated norms; PF is the penalty function, which provides conditions of stability during optimization process; $\mathbf{K}$ is the vector of the control law coefficients.

Presence of performance indices both for deterministic and stochastic cases in the expression (1) is explained by the conflict situation between the necessity to satisfy requirements to system performance in conditions of stochastic coordinate disturbances and deterministic control signals. On the one hand, to improve reaction on deterministic control signals it is necessary to increase gains of open-loop system. This increases bandwidth of closed loop system. On the other hand, increasing bandwidth decreases filtering properties and the ability of attenuation of the high-frequency noise and disturbances.

Choice of coefficients $\lambda_2^{\text{nom d}}, \lambda_2^{\text{nom s}}$ allows achieving the required accuracy of the system in conditions of stochastic disturbances (irregular sea waves). Usage of H_∞-norm of the function of complementary sensitivity of the nominal system with the weighting coefficient $\lambda_\infty^{\text{nom}}$ allows achieving the compromise between system accuracy and robustness.

So, search of compromise during optimization procedure execution is providing by the optimization criterion (1) using variations of weighting coefficients. Such approach to optimization problem solution is called multi-purpose [6], because it provides search of compromise between different conflicting goals.

To develop procedure of parametric optimization it is necessary to take into consideration the system features. These features for researched system are as follows.

1. Optimization procedure of the researched system requires minimal realization. It can be done based on state space model. Rosenbrock algorithm is the most acceptable in this case [8]. As result the researched system can be reduced to observable and controllable one. The minimal realization of the system model can be implemented based on function *mineral*, which belongs to Control System Toolbox [9].

2. The state space model of the researched system is ill-conditioned as components of the state matrix $\mathbf{A}$ are characterized by great range of numerical values. Usually such matrices are ill-conditioned in practical problems relative to procedure of eigenvalues determination. To eliminate this disadvantage it is necessary to determine balanced realization of the system model. Such realization is characterized by equal gramians of observability and controllability. It can be implemented by MATLAB function *obalreal* [9].

3. The procedure of the parametric optimization is carried out in two stages. The parametric optimization in essence is carried out at the first stage. It is based on the state space models created by means of Control System Toolbox. Checking obtained results is carried out at the second stage. Such a check is implemented by means of mathematical model, which as much as possible takes into consideration all nonlinearities inherent to real systems. Usually Simulink Toolbox is used for creation of such models.

Coefficients of control laws are parameters to be optimized in the procedure of optimization of navigation loops of the precision attitude and heading reference system. The interactive procedure of navigation loop design consists of the following stages.

1. Determination of the kind of a control law depending on the system operating mode based on experience of design of the researched type system.

2. The choice of coefficients of control law as optimization parameters.

3. Determination of restrictions on the control laws coefficients in order to simplify the optimization procedure.

4. Development of the full mathematical model of the navigation loop (control law) depending on operating mode taking into consideration all the nonlinear components. To simplify the mathematical model of the navigation loop, equations of the gyroscopes motion are believed to coincide with equations of the platform motion. Accuracy of this supposition is defined by error of the system stabilization.

5. Linearization of the developed model taking into consideration typical nonlinearities, first of all, trigonometric functions, which describe the kinematics of the system.

6. Creation of the mathematical description in the state space taking into consideration features of operating mode.
7. Determination of minimal realization.
8. Model scaling based on algorithm of balanced realization.
9. Determination of initial values and usage of the genetic algorithm with cycling execution of the following steps:
   – determination of the systems poles and their location on the plane of the complex variable and determination of the respective penalty function;
   – calculation of the complex optimization criterion.
10. Analysis of the synthesized system including following steps:
   – calculation of H_2, H_∞-norms of the synthesized system;
   – analysis of indices of the transient processes using models with nonlinearities inherent to real systems.
11. Conclusion about stopping procedure of the parametric optimization or its continuing with new initial values or weighting coefficients of the complex optimization criterion (1).

5. Robust structural synthesis

In the general case, the robust structural synthesis of the control system is based on solution of two Riccati equations, checking some conditions [10] and minimization of H_∞-norm of the mixed sensitivity function of the system which includes the plant $\mathbf{G}$ and the controller $\mathbf{K}$. This system is characterized by the vector of outputs $\mathbf{z}$, which defines the system quality, by the vectors of inputs $\mathbf{r}$, controls $\mathbf{u}$ and observations $\mathbf{y}$.

The modern approach to solution of the robust structural H_∞-optimization is based on shaping of the desirable frequency characteristics of the designed system (loop-shaping). Such approach is implemented by means of forming the augmented plant using the weighting transfer functions.

H_∞-norm of the mixed sensitivity function of the augmented system is used as the optimization criterion [10, 11]

$$J_{H_\infty} = \left\| \begin{bmatrix} \mathbf{W}_1\mathbf{S} \\ \mathbf{W}_2\mathbf{R} \\ \mathbf{W}_3\mathbf{T} \end{bmatrix} \right\|_\infty , \qquad (2)$$

here $\mathbf{W}_1, \mathbf{W}_2, \mathbf{W}_3$ are the weighting transfer functions, $\mathbf{S}, \mathbf{R}, \mathbf{T}$ are the sensitivity function, the control sensitivity function and the complementary sensitivity function.

The statement of the structural H_∞-synthesis by the method of the mixed sensitivity can be explained by the structural scheme which is represented in Fig. 2.

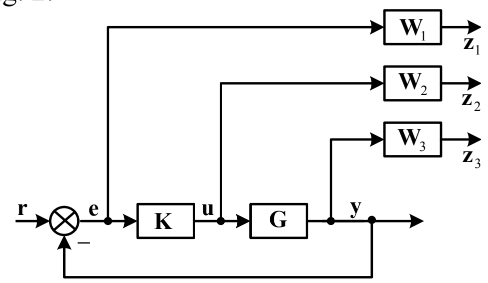


Fig. 2. H_∞-optimization by the method of the mixed sensitivity

Such instrument of the computer-aided design as the Robust Control Toolbox includes functions for the structural synthesis by the method of the mixed sensitivity. These functions (*augtf*, *hinfopt*) provide creation of the augmented model and execution of the H_∞-synthesis design procedure based on the optimization criterion (2) [11]. Efficiency of the H_∞-synthesis by the method of the mixed sensitivity essentially depends on the choice of the weighting transfer functions. In many cases, the choice of these functions is carried out by the empiric methods taking unto account experience of the similar systems development.

Weighting function used for loop shaping of the researched system look like

$$W_1 = 1200\frac{0{,}07s+1}{0{,}015s+1}\frac{0{,}05s+1}{s+0{,}01}\frac{0{,}1s+1}{0{,}1s+0{,}01},$$

$$W_2 = 0{,}01_2,\ W_3 = s^2 .$$

As a rule, the controller synthesized by the method of the mixed sensitivity represents a system of the high order. There are some approaches [11] to reduction of the synthesized controllers such as reduction of the system model before the H_∞-synthesis procedure, reduction of the system model after the H_∞-synthesis procedure and use of the special methods which provide creation of the system with the reduced order.

The comparative analysis had been shown that the reduction of the synthesized controller is convenient to carry out after the H_∞-synthesis procedure termination. The reduction of the controller of the studied system can be carried out by means of the function *balmr* [11].

The studied gimballed system for the marine vehicle navigation by its principle of operation represents the indicated or indirect inertially stabilized platform. In such systems the gyroscopic devices do not implement direct stabilization of some object, for example, the platform but represent indicator units, which control by the servo drive providing object's stabilization [12].

In such systems compensation of disturbances that influence on the stabilized platform is implemented due to moments created by actuators mounted at the gimbals axes. Control by the stabilization loops is carried out by the gyroscopic devices signals, which, in its turn, are corrected by the accelerometers signals.

In the researched system control loops can be divided into navigation and stabilization ones that allows creating separate procedures of their design. Division of control functions is implemented in the following way. The stabilization engines provide agreement of the stabilization plant and gyroscopic devices positions and the torques sensors implement correction of the rotor motion by the computing device based on accelerometers signals and data about the Earth and object motion.

If angles of the roll and pitch are small, it is possible to neglect by the mutual influence of gimbals and consider stabilization process on example of one channel.

As the dynamically tuned gyro is used as the sensible element of the inertially stabilized platform, it is necessary to take into consideration that it operates in the indicated mode.

Such a mode does not require the high stability of the transfer coefficient but the sensitivity is very important. It means that the large slope of the static characteristic curve near zero and the low threshold of sensitivity must be provided.

These factors lead to small angles of the rotor turns and correspondingly to the small operation range. Therefore to improve stabilization accuracy it is necessary to use the units which sufficiently increase the stabilization loop gain. Moreover, taking into consideration the operation principle of the dynamically tuned gyro it is necessary to use the selective filter [13].

For the studied system the basic disturbance moment can be described by the expression

$$M_{db} = M_0 + M_{fr}\mathrm{sign}(\sin \omega t) + M_s \sin \omega t ,$$

here M_0 is the constant disturbance moment caused by the construction defects; M_{fr} is the moment of dry friction; M_s is the amplitude of the moment due to sea regularities; ω is the frequency of the sea regularities.

6. Results of design procedure execution

Results of robust parametric optimization of navigation loop are given in Table 1.

Table 1

Coefficients of control laws in navigation loops

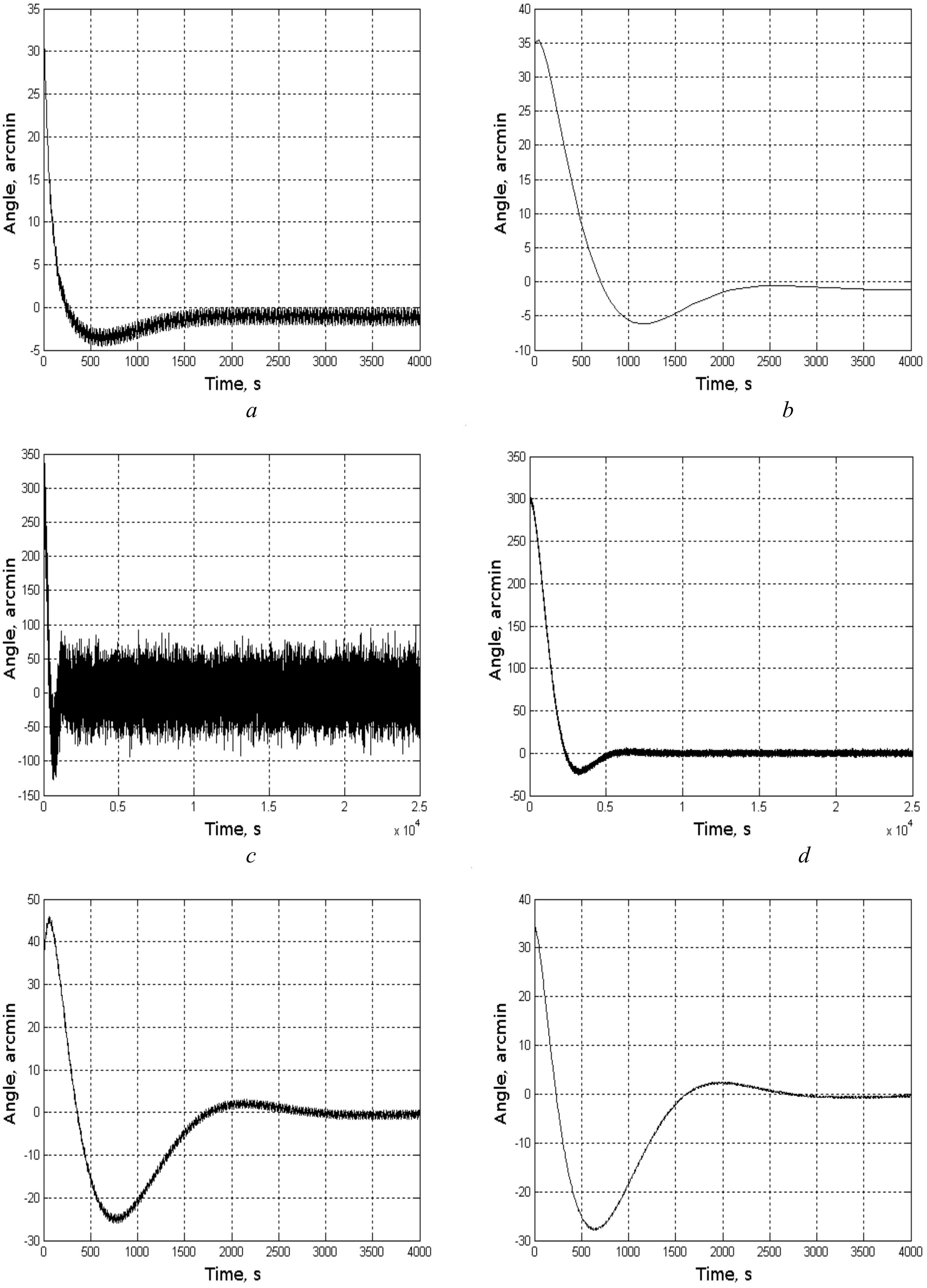
Coefficient	Value	Mode	Correction
k_1	4,5	Preliminary levelling	Accelero-meters
k_2	4,5	“-“	“-“
k_3	3,5	“-“	“-“
k_4	3,5	“-“	“-“
k_5	0,3	“-“	“-“
k_6	0,3	“-“	“-“
k_7	1,2	“-“	“-“
k_8	1,2	“-“	“-“
k_9	1,2	“-“	“-“
$k_{пх}$	3,2	Precision levelling	Accelero-meters, log, DTGs
$k_{пу}$	3,1	“-“	“-“
$k_{дмх}$	0,3	“-“	“-“
$k_{дму}$	0,34	“-“	“-“
k_x	0,2	“-“	“-“
k_y	0,4	“-“	“-“
$k_{пх}$	5,2	Gyroscopic compass	Accelero-meters, log, DTCs
$k_{пу}$	5,1	“-“	
$k_{дмх}$	0,35	“-“	
$k_{дму}$	0,33	“-“	
k_x	0,27	“-“	
k_y	0,41	“-“	
k_1	0,0003	“-“	
k_2	0,001	“-“	

It should be noted that expressions of control laws in navigation loops are given in the paper [5].

The transient processes in the modes of preliminary alignment in the horizon plane and the mode of the gyroscopic compass are given in Fig. 3.

The synthesized navigation loop in the mode of levelling is characterized by norms $H_\infty = 0{,}1224$ and $H_2 = 0{,}0054$ respectively. The synthesized navigation loop in the mode of gyroscopic compass is characterized by norms H_∞=0,0081 and H_2=3,8·10^{-4}.

Results of stabilization loop synthesis are as follows.


Angle, arcmin
Time, s
35
30
25
20
15
10
5
0
-5
0
500
1000
1500
2000
2500
3000
3500
4000
40
-10
350
300
250
200
150
100
50
-50
-100
-150
0.5
1
1.5
2
2.5
x 10^4
-20
-30

a *b*

c *d*

e *f*

Fig. 3. Transient process in the mode of precision levelling by the pitch for nonoptimized (a) and optimized (b) systems; transient process in the mode of gyroscopic compass by the heading for nonoptimized (c) and optimized (d) systems and by the pitch for nonoptimized (e) and optimized (f) systems

The synthesized controller can be described by state space matrices reduced from 10th to 7th order

$$A=\begin{bmatrix} -1{,}36 & 54{,}17 & 1{,}11 & -98{,}9 & 10{,}75 & -0{,}07 & 3{,}55 \\ 78{,}7 & -221{,}9 & 12{,}42 & 512{,}3 & -145{,}5 & 96{,}18 & -0{,}76 \\ 11{,}62 & 28{,}72 & 1{,}58 & -50{,}17 & -0{,}54 & 7{,}06 & 3{,}29 \\ -198{,}4 & 162{,}4 & -68{,}61 & -551{,}1 & 140{,}1 & -194{,}8 & -4{,}01 \\ 84{,}63 & 192{,}1 & 59{,}36 & -293{,}5 & 59{,}6 & 17{,}05 & 20{,}66 \\ -4{,}2 & -125{,}3 & -10{,}33 & 224{,}1 & -52{,}15 & -36{,}82 & -5{,}11 \\ 55{,}2 & 226{,}3 & 39{,}1 & -172{,}9 & 116{,}2 & 157{,}9 & -105{,}8 \end{bmatrix};$$

$$B^T=\begin{bmatrix} 0{,}23 & 0{,}77 & -0{,}32 & -1{,}04 & 0{,}3 & -0{,}07 & 0{,}57 \\ -7{,}33 & -104{,}4 & -13{,}36 & 208{,}8 & -55{,}92 & 14{,}23 & -87{,}19 \end{bmatrix};$$

$$C=\begin{bmatrix} 0{,}88 & 4{,}48 & 0{,}84 & -8{,}31 & 2{,}68 & -0{,}53 & 0{,}22 \end{bmatrix};$$

$$D=[0 \quad 0].$$

The platform srabilization processes are represented in Figures 4, 5.

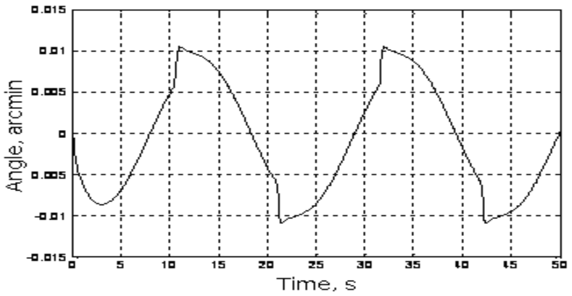


Fig. 4. The stabilisation dynamic error due to influence of friction moment

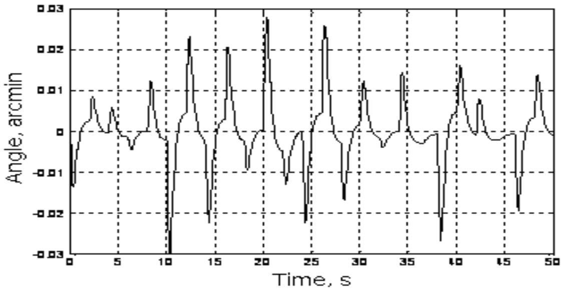


Fig. 5. The stabilisation dynamical error due to influence of irregular sea wave (3 points)

Influence of the irregular sea waves was simulated by means of the forming filters taking into consideration information about spectral densities of these disturbances [14]. Analysis of the obtained results shows that the synthesized system is resistant to the coordinate disturbance in comparison with the non-optimized system (Fig. 3).

Results represented in Figures 4, 5 show that the synthesized system provides high speed of operation and accuracy of stabilization. The small dynamic errors in conditions of disturbances prove the high dynamic characteristics of the designed system.

7. Conclusions

The design procedures of navigation and stabilization loops based on robust parametric H_2/H_∞-optimization and robust structural H_∞-synthesis are developed. The coefficients of navigation laws and robust controller structure are obtained. The results of simulation of synthesized navigation and stabilization loops are represented.

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Проектування робастних навігаційних та стабілізаційних контурів високоточної системи визначення просторової орієнтації

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Мета: У статті розглянуто проблеми проектування робастних високоточних систем визначення просторової орієнтації, які можуть використовуватися у навігації морських рухомих об'єктів. Головною метою є створення оптимізаційних процедур проектування навігаційних та стабілізаційних контурів багаторежимної платформної системи. Оптимізаційна процедура проектування навігаційного контуру заснована на параметричній робастній H_2/H_∞-оптимізації. Оптимізаційна процедура проектування контуру стабілізації заснована на робастному структурному H_∞-синтезі. **Методи дослідження:** Для розв'язання даної проблеми було використано теорію робастних систем управління та оптимізаційні методи. **Результати:** Представлено кінематичну схему системи визначення просторової орієнтації. Наданий алгоритм параметричної оптимізації з урахуванням особливостей досліджуваної системи. Визначено закони управління навігаційних контурів на підставі оптимізаційної процедури, що забезпечує компроміс між точністю та робастністю системи. Розроблено робастний регулятор стабілізаційного контуру на підставі методу змішаної чутливості. Виконано імітаційне моделювання процесів навігації та стабілізації. **Висновки:** Представлені результати підтверджують ефективність запропонованих процедур, які можуть бути корисними для проектування навігаційних систем рухомих об'єктів.

Ключові слова: високоточна навігація; метод змішаної чутливості; робастна параметрична оптимізація; робастний структурний синтез; система визначення просторової орієнтації.

О.А. Сущенко

Проектирование робастных навигационных и стабилизационных контуров высокоточной системы определения пространственной ориентации

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Цель: В статье рассмотрены проблемы проектирования робастных высокоточных систем определения пространственной ориентации, которые могут быть использованы в навигации морских подвижных объектов. Главной целью является создание оптимизационных процедур проектирования навигационных и стабилизационных контуров многорежимной платформенной системы. Оптимизационная процедура проектирования навигационного контура основана на параметрической робастной H_2/H_∞-оптимизации. Оптимизационная процедура проектирования контура стабилизации основана на робастном структурном H_∞-синтезе. **Методы исследования:** для решения данной проблемы были использованы теория робастных систем управления и оптимизационные методы.

Результаты: Представлена кинематическая схема системы определения пространственной ориентации. Представлен алгоритм параметрической оптимизации с учетом особенностей исследуемой системы. Определены законы управления навигационных контуров на основании оптимизационной процедуры, обеспечивающей компромисс между точностью и робастностью системы. разработан робастный регулятор стабилизационного контура на основании метода смешанной чувствительности. Выполнено имитационное моделирование процессов навигации и стабилизации. **Выводы:** Представленные результаты подтверждают эффективность предложенных процедур, которые могут быть полезными для проектирования навигационных систем подвижных объектов.

Ключевые слова: высокоточная навигация; метод смешанной чувствительности; робастная параметрическая оптимизация; робастный структурный синтез; система определения пространственной ориентации.

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