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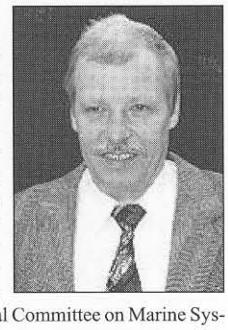
High Precision State Feedback Robust Control System For Ship Track-Keeping



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Stopień magistra matematyki uzyskał w roku 1974 na Uniwersytecie Łódzkim, w 1979 stopień doktora nauk technicznych na Wydziale Elektrycznym Politechniki Szczecińskiej. Stopień naukowy doktora habilitowanego uzyskał w roku 2000 na Wydziale Oceanotechniki i Okrętownictwa Politechniki Gdańskiej. W roku 2001 został profesorem nzw. Wydziału Mechanicznego Politechniki Koszalińskiej, a od roku 2003 jest profesorem nzw. Wydziału Elektrycznego Politechniki Szczecińskiej. Zajmuje się teorią sterowania, opisem systemów w dziedzinie częstotliwości, układami nieliniowymi, autopilotami. Jest członkiem: IFAC Technical Committee on Marine Systems, SIAM Activity Group in Control Theory, American Mathematical Society oraz Polskiego Towarzystwa Matematycznego.

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Abstract

In the paper the problem of ship trajectory tracking with *ε-accuracy* is considered. A three-degrees-of-freedom ship model with full dynamic interaction between motions in roll, sway and yaw is assumed. The aim of the paper is to determine the robust control for ship trajectory tracking with *ε-accuracy*. Such control is obtained by means of a state feedback (called Tytus feedback) system characterised by an arbitrarily high gain. For this purpose a non-linear as well as linearised stable and unstable ship model is used. The simulation results confirm that a high precision performance can be achieved by the proposed control scheme.

Streszczenie

W pracy rozważa się problem sterowania ruchem statku po zadanej trajektorii z dowolnie małą *ε-dokładnością*. W rozważaniach przyjęto model statku o trzech stopniach swobody i pełnym opisie zależności dynamicznych pomiędzy przechyłami bocznymi, kołysaniem wzdłużnym i kursem statku. Celem pracy jest wyznaczenie odpornego układu sterowania ruchem statku po zadanej trajektorii z *ε-dokładnością*. Układem spełniającym powyższe warunki jest układ ze sprzężeniem zwrotnym od stanu i dostatecznie dużym wzmocnieniem. Opisany układ ze sprzężeniem zwrotnym wykorzystano do sterowania nieliniowego modelu statku jak również dla sterowania zlinearyzowanego, stabilnego i niestabilnego modelu statku. Wyniki symulacji w środowisku MATLAB-SIMULINK potwierdzają wysoką jakość sterowania jaka może być uzyskana dzięki wykorzystanie zaproponowanego układu.

Keywords: tracking systems, multivariable systems, feedback control, marine systems
Słowa kluczowe: układy śledzące, wielowymiarowe układy ze sprzężeniem zwrotnym, automatyka morska

1. Introduction

The remarkable growth in transport of passenger and cargo at sea as well as the monitoring and exploitation of ocean resources has determined the construction of an increasing number of new surface ships and underwater vehicles. For efficient operation at sea, it is essential that these craft should be equipped with advanced control systems. Control systems to be installed on board ships are generally designed in such a way as to reduce fuel consumption, to minimise disturbing wave induced motion and at the same time to improve navigation accuracy. It has been verified in recent years that traditional control methods are generally inadequate for designing efficient control systems.

Design solutions for marine craft motion control are often rather difficult to find within the framework of classical control theory, owing to the intrinsic non-linear dynamic behaviour of the plant itself and to the disturbances, which act upon it. Many research and simulation studies have been conducted in recent years in order to design and put into operation a new generation of ship control systems, such as autopilots, stabilisers and dynamic positioning systems, capable of efficiently and safely carrying out demanding navigation tasks in a widely varying range of environmental conditions. In principle, the design of such control systems should be based on a multivariable approach, which takes proper account of the couplings between the different motion and determines control systems within the framework of optimal control theory. A number of successful simulation studies and sea trials have been carried out which apparently supported such an approach.

It is worth and surprisingly enough noting, however, that the adoption of these optimal designs has been until now quite rare on board new ships, where old fashioned PID autopilots are often still preferred. This apparent discrepancy is partly due to the fact that most of the proposed designs are critically dependent on the availability of accurate mathematical models of the ship and environment, which are generally quite complex and difficult to determine and properly implement on-line tuning. It is therefore attractive proposition to explore the applicability of robust control methods, which potentially can reduce the negative effects on the control system performance of the uncertain factors affecting the ship dynamic behaviour. Most of these methods can be derived by an H_∞ optimisation approach, which aims at satisfying the control specifications with a significant rejection of disturbances. It has been shown that this corresponds, in the linear case, to the determination of a stabilising feedback controller that minimises the infinity-norm of a properly weighted system transfer matrix. The weights are chosen in such a way as to cope with the main uncertainties affecting the system.

In this paper a novel algorithm for determining a robust control strategy for the ship multivariable track-keeping problem is presented. This algorithm, based on a functional analysis approach, reduces the computational complexity, which generally does not allow an efficient implementation of robust control methods, such as for example in the case of μ-synthesis, in multivariable systems. Simulation results are presented that confirm the achievable and excellent performance of the proposed control system. These results have been obtained after simulation experiments based on a non-linear ship, model previously determined from towing tank and sea trials experiments.

2. Ship mathematical models

For the ship motion analysis it is useful to consider the two co-ordinate systems shown in Fig. 1. The first one $X_oY_oZ_o$ is chosen in the earth-fixed point, while the second XYZ in the centre of symmetry of the hull. Pitch and heave motions will be neglected, taking into account that they are uncoupled with longitudinal plane motions. We will take under consideration the ship motion in three degrees of freedom relating the coupled sway, yaw, and roll response to the rudder at a constant cruising speed.

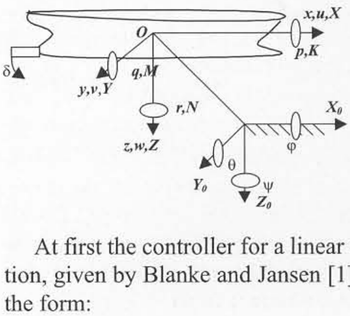

Fig. 1. Ship co-ordinate system
Rys. 1. Układ współrzędnych statku

At first the controller for a linear and unstable model of ship motion, given by Blanke and Jansen [1] is determined. This model has the form:

$$\begin{bmatrix}\dot v\\ \dot r\\ \dot p\\ \dot\varphi\\ \dot\psi\end{bmatrix}=\begin{bmatrix}-0.0122 & -4.4802 & -0.0300 & -0.0256 & 0\\ -0.0012 & -0.2211 & -0.0062 & -0.0009 & 0\\ 0.0025 & -0.6504 & -0.0252 & -0.0282 & 0\\ 0 & 0 & 1 & 0 & 0\\ 0 & 1 & 0 & 0 & 0\end{bmatrix}\begin{bmatrix}v\\ r\\ p\\ \varphi\\ \psi\end{bmatrix}+\begin{bmatrix}0.1315\\ -0.0050\\ -0.0043\\ 0\\ 0\end{bmatrix}\delta$$

$$\begin{bmatrix}p\\ \psi\end{bmatrix}=\begin{bmatrix}0 & 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 0 & 1\end{bmatrix}\begin{bmatrix}v\\ r\\ p\\ \varphi\\ \psi\end{bmatrix} \tag{1}$$

There are two unstable eigenvalues.

Equations (1) are a straightforward linearisation of the non-linear model for a ship speed of 12.5 m/s and ship's metacentric height GM=83 cm. The control system designed for the model expressed by equations (1) is then compared with a control system for the parameter tuned model given by equation (2)

$$\begin{bmatrix}\dot v\\ \dot r\\ \dot p\\ \dot\varphi\\ \dot\psi\end{bmatrix}=\begin{bmatrix}-0.0115 & -3.2325 & -0.1112 & -0.0694 & 0\\ -0.0010 & -0.2216 & -0.0066 & -0.0010 & 0\\ 0.0037 & 0.0960 & -0.0752 & -0.0552 & 0\\ 0 & 0 & 1 & 0 & 0\\ 0 & 1 & 0 & 0 & 0\end{bmatrix}\begin{bmatrix}v\\ r\\ p\\ \varphi\\ \psi\end{bmatrix}+\begin{bmatrix}0.1217\\ -0.0050\\ -0.0103\\ 0\\ 0\end{bmatrix}\delta$$

$$\begin{bmatrix}p\\ \psi\end{bmatrix}=\begin{bmatrix}0 & 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 0 & 1\end{bmatrix}\begin{bmatrix}v\\ r\\ p\\ \varphi\\ \psi\end{bmatrix} \tag{2}$$

This model has all stable eigenvalues. The designed control systems for the above linear models will be subsequently used for controlling with *ε-accuracy* the non-linear model proposed by Blanke and Jensen [1].

In analysing the ship motion control system we must also take into consideration the mathematical model of the steering machine. The rudder angle and rudder rate boundary result from the characteristic of the steering machine. Typical constraints are in the ranges:

$|\delta| \le \delta_{max} \approx 35$ deg, $|\dot\delta| \le \dot\delta_{max1} = 2.3$ deg/s or $|\dot\delta| \le \dot\delta_{max2} = 4,6$ deg/s (3)

These constraints will be used for determining the class of admissible reference signals (class of given ship trajectories) $L^2\{W\}$ or more generally $R\{W\}$, described in the next section.

3. High precision state feedback control system

The systems presented in the paper enable control with *ε-accuracy* for a stable or unstable plant P described by a high order differential equation. This can be done by using a state feedback (called here Tytus feedback) presented in the following part.

Let us consider a set of signals X regarded as a Banach space. For example X can be the set of signals with bounded energy L^2, or the set of signals with bounded mean power M (Marcinkiewicz space). Let a plant, given by operation $y(t)=P(u(t))$, transform any set of signals $W\subset X$ into X. We assume that operation P is a composition as shown in equation:

$$P=P_n(...(P_2(P_1))) \tag{4}$$

for the operations $x_1(t)=P_1(u(t))=P_1(x_o(t))$, $x_i(t)=P_i(x_{i-1}(t))$, i=2, ..., n. We assume that P_i transform the sets of signals $W_i\subset X$ into X. Let the operation P be given by the set of equations

$$\begin{cases} x_1(t)=P_1(x_o(t))\\ x_2(t)=P_2(x_1(t))\\ \quad\ddots\\ x_n(t)=P_n(x_{n-1}(t))\\ y(t)=x_n(t)\end{cases} \tag{5}$$

In the particular case the variables $\chi(t)=[x_1(t), x_2(t), ..., x_n(t)]^T$ can be considered as the state variables of the operation P. We will denote them by $\chi(t)=P(u(t))$.

Taking into consideration the state feedback control system described by equations

$$\begin{cases} u(t)=ke(t)\\ \delta(t)=\chi_0(t)-P(u(t))\\ \chi_0(t)=P(u_0(t))\end{cases} \tag{6}$$

where $\chi_o(t)=[x_{o1}(t), x_{o2}(t), ..., x_{on}(t)]^T$, $y_o(t)=x_{on}(t)$ are reference signals, $e_i(t)=x_{oi}(t)-x_i(t)$, $\delta(t)=[e_1(t), e_2(t), ..., e_n(t)]^T=\chi_o(t)-\chi(t)$, i=1, 2, ..., n, $e(t)=\sum_{i=1}^{n} e_i(t)$, are error signals, $u(t)=x_o(t)$ is the control signal. The scheme of such system (Tytus system) is shown in Fig. 2.

Furthermore, let the operation P be one-to-one, then the "ideal" control system should be a system generating (for any signal y_o) a control signal $u=P^{-1}(y_o)$.

We denote by $X\{P,m\}$ a set of all signals $y_o(t)\in X$ such that the operation P and constant $0<m<\infty$ satisfy the relations

$$P^{-1}(y_o)\in X \text{ and } \|P^{-1}(y_o)\|_X \le m<\infty \tag{7}$$

i.e. $X\{P,m\}=\{\, y_o(t)\in X\colon P^{-1}(y_o)\in X$ and $\|P^{-1}(y_o)\|_X \le m<\infty\}$

If the constant m is not determined exactly then the notation $X\{P\}$ will be used.

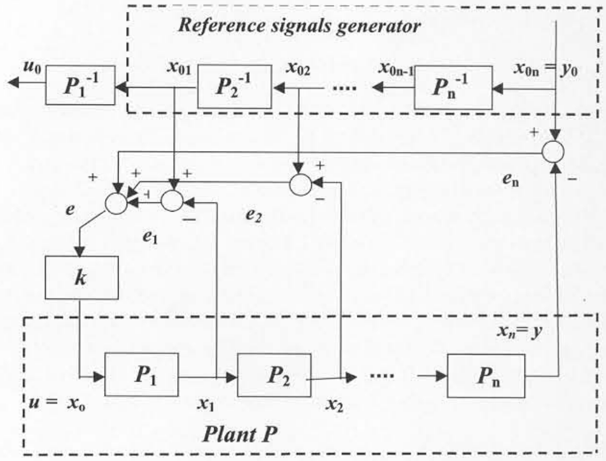

Fig. 2. Feedback system controlling the plant $P=P_n(...(P_2(P_1)))$ with *ε-accuracy*
Rys. 2. Układ sterujący obiektem $P=P_n(...(P_2(P_1)))$ z *ε-dokładnością*

Definition 1: The plant P is controlled with *ε-accuracy* to signals $y_o(t)\in X\{P,m\}$ by the system (3) if there exist such constants k_1, k_2 (k_1, k_2 depend on ε) that for every $k\in[k_1,k_2)$ the inequality

$$\|e_n\|_X \le \varepsilon \tag{8}$$

is satisfied.

At first, we take under consideration the system (6) as a particular case, when $P_i=P$ (i=1). If the operation P_i is one-to-one, then the "ideal" control system is a system generating, for any signal $x_{oi}\in X\{P_i\}$, the control signal $x_{i-1}=P_i^{-1}(x_{oi})$. We assume that the operation P_i transforms the set of signals $X\{P_i\}$ into Banach space X. Let k be a real number ($k\in\Re$). The first two equations of (6) can be written in the form

$$x_{oi}-P_i(x_{i-1})=\frac{1}{k}x_{i-1} \tag{9}$$

for any given point $x_{oi}\in X\{P_i\}$. In order to use Graves theorem [2] we rewrite the equation (9) in the form

$$H(x,y)=H(x_{i-1},x_i)=x_{oi}-P_i(x_{i-1})-\frac{1}{k}x_{i-1} \tag{10}$$

If relation (10) satisfies the assumptions of Graves theorem, then mapping $H(x_{i-1},x_i)$ generates the implicit operation

$$X \ni G_k(x_{oi})=x_{i-1}\in X,\quad k\in[k_1,\infty) \tag{11}$$

Additionally, let us assume that the mapping P_i is continuous, one-to-one and that there exists a continuous inverse operation $x_{i-1}=P_i^{-1}(x_i)$. Under the above conditions, for any point $x_{oi}\in X\{P_i\}$, there exist two points x_{oi-1}, $x_{*i-1}\in X$ such that:

$$x_{oi}-P_i(x_{*i-1})-\frac{1}{k}x_{*i-1}=0 \tag{12a}$$

$$x_{oi}-P_i(x_{oi-1})=0 \tag{12b}$$

or

$$G_k(x_{oi})=x_{*i-1} \tag{13a}$$

$$P_i^{-1}(x_{oi})=x_{oi-1} \tag{13b}$$

where $G_k(x_{oi})$ is the implicit mapping generated by equation (10). In this case, the Definition 1 is equivalent to the Definition 1'.

Definition 1': The plant P_i is controllable with *ε-accuracy* to reference signals $x_{oi}(t)\in X\{P_i,m\}$ by the system expressed by (6), if there exist constants k_1, k_2 (k_1, k_2 depending on ε) such that for every $k\in[k_1,k_2)$ there exists an implicit mapping $G_k(x_{oi})=x_{*i-1}$ generated by (10) such that the inequality

$$\left\|G_k(x_{oi})-P_i^{-1}(x_{oi})\right\|_X\le\varepsilon \tag{14}$$

is satisfied.

Theorem 1. ([3], [4]): Let the operation P_i transform a set of signals $X\{P_i\}$ into space X and P_i fulfil the conditions:

1°. for every $x_{oi}(t)\in X\{P_i\}$ exists $x_{*i-1}(t)\in X$ such that $x_{oi}-P_i(x_{*i-1})-\frac{1}{k}x_{*i-1}=0$

2°. $P_i(x_{i-1})$ is continuously differentiable

3°. $\left(P'_{i\,x}(x_{*i-1})+\frac{1}{k}\right)^{-1}\in L(X.X)$ for every $k\in[k_1,\infty)$

then the system described by equations (6) controls the plant P_i with *ε-accuracy* for $x_{oi}(t)\in X\{P_i\}$ and $k\in[k_1,k_2)$.

Let the operation P_i mapping a set of signals from Banach space X into itself be linear, causal and stationary. Now let X be a Banach space L^2 (or space M). We assume that operation P_i is given by the formula

$$[P_i x_{i-1}](t)=\int_0^t x_{i-1}(t-\tau)dh_i(\tau) \tag{15}$$

where $h_i(\tau)$ is a bounded variation function, or by a transfer function $P_i(s)$. We rewrite equation (6) in the form

$$\frac{1}{k}x_{i-1}(t)=x_i(t)-\int_0^t x_{i-1}(t-\tau)dh_i(\tau) \tag{16}$$

Theorem 2. If for a number $k\in[k_1,k_2)$, where k_1, k_2 are sufficiently large, and for the operation P_i the inequality

$$\inf_{res\ge0}\left|\frac{1}{k}+P_i(s)\right|>0 \tag{17}$$

is satisfied, then the system given by equations (15), (16) controls the plant P_i with *ε-accuracy* for a reference signal $x_{oi}(t)\in L^2\{P_i\}$ ($x_{oi}(t)\in M\{P_i\}$).

Theorem 2 is a particular case of the Theorem 1.

Formula (17) in Theorem 2 has the following geometrical interpretation: The system described by equations (15) and (16) controls a plant P_i with *ε-accuracy* for a class of input signals $L^2\{P_i\}$ (or $M\{P_i\}$) if the spectrum of operation $P_i(s)$ and interval $\left[-\frac{1}{k_1},-\frac{1}{k_2}\right)$ are disjoint sets.

4. System with state feedback

Now we take under consideration the superposition P of operations P_i given by the formula (4) and (5). If we put (4) and (5) into equation (6), we get

$$u(t)=k\{(P_2^{-1}(x_{o2}(t))-P_1(u(t)))+(P_3^{-1}(x_{o3}(t))-P_2(P_1(u(t))))+\dots$$
$$\dots+(x_{on}(t)-P_n(\dots(P_1(u(t)))))\}$$

$$\delta(t)=[P_2^{-1}(x_{o2}(t))-P_1(u(t)),\ P_3^{-1}(x_{o3}(t))-P_2(P_1(u(t))),\ \dots,$$
$$\dots,\ x_{on}(t)-P_n(\dots(P_1(u(t))))]' \tag{18}$$

$$\chi_o(t)=[P_1(u_o(t)),\ P_2(P_1(u_o(t))),\ \dots,\ P_n(\dots(P_1(u_o(t))))]'=$$
$$=[P_2^{-1}(x_{o2}(t)),\ P_3^{-1}(x_{o3}(t)),\ \dots,\ x_{on}(t)]'$$

Equation (6) for the linear, causal and stationary plant takes the form:

$$\begin{bmatrix}1\\1\\\dots\\1\end{bmatrix}u(s)=k\begin{bmatrix}1&1&\cdots&1\\1&1&\cdots&1\\\dots&\dots&\dots&\dots\\1&1&\cdots&1\end{bmatrix}\begin{bmatrix}e_1(s)\\e_2(s)\\\dots\\e_n(s)\end{bmatrix}$$

$$\begin{bmatrix}e_1(s)\\e_2(s)\\\dots\\e_n(s)\end{bmatrix}=\begin{bmatrix}x_{o1}(s)\\x_{o2}(s)\\\dots\\x_{on}(s)\end{bmatrix}-\begin{bmatrix}P_1(s)&0&\cdots&0\\0&P_1(s)P_2(s)&\cdots&0\\\dots&\dots&\dots&\dots\\0&0&\cdots&P_1(s)P_2(s)\cdots P_n(s)\end{bmatrix}\begin{bmatrix}1\\1\\\dots\\1\end{bmatrix}u(s) \tag{19}$$

$$\begin{bmatrix}x_{o1}(s)\\x_{o2}(s)\\\dots\\x_{on}(s)\end{bmatrix}=\begin{bmatrix}P_2^{-1}(s)\cdots P_n^{-1}(s)&0&\cdots&0\\0&P_3^{-1}(s)\cdots P_n^{-1}(s)&\cdots&0\\\dots&\dots&\dots&\dots\\0&0&\cdots&1\end{bmatrix}\begin{bmatrix}1\\1\\\dots\\1\end{bmatrix}y_o(s)$$

Formally, for $k\to\infty$, the system shown in Fig. 2 controls the plant P with *ε-accuracy*. The following theorem can be proved.

Theorem 3: If all of the operations:
P_1: $W\to X\{P_1\}\subset X$, P_i: $X\{P_{i-1}\}\to X\{P_i\}\subset X$, $i=2, 3, \dots, n$ satisfy assumptions of the Theorem 1, then superposition of P given by formulae (4) also satisfies the assumption of Theorem 1 and the system shown in Fig. 2 controls plant P with *ε-accuracy*.

5. Ship trajectory tracking

Now taking into consideration the control system given by equation (6), let the control signal $u(t)$ consist of the rudder angle in time $\delta(t)$. We will assume that plant P consists of the ship motion model and the steering machine. Also it is assumed that we do not know exactly the ship speed on the reference ship trajectory.

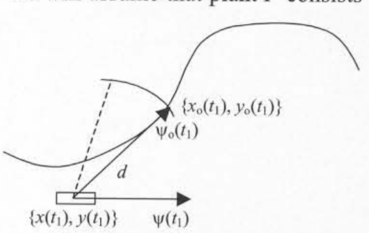

Fig. 3. Track of ship trajectory
Rys. 3. Śledzenie trajektorii statku

As a reference signal we take the vector $\boldsymbol{r}(t)=[\psi_o(t),\ p_o(t)]^T$. Coefficient $p_o(t)$ is connected with the roll angle $\varphi(t)$ and it will be assumed that $p_o(t)=0$. The first coefficient $\psi_o(t)$, is connected with ship heading angle $\psi(t)$. It can be determined in the following way: let point $\{x(t_l),y(t_l)\}$ denote the actual ship position in the system axis X_o,Y_o (see Fig. 1), at the instant t_l. We denote $\{x_0(t_l),y_0(t_l)\}$ as the point which lies on the assumed ship trajectory at a distance d from $\{x(t_l),y(t_l)\}$ to $\{x_0(t_l),y_0(t_l)\}$. The distance d should be constant for every time instant t. In other words, the point $\{x_0(t),y_0(t)\}$ is an intersection point of the assumed ship trajectory and the circle with radius $d(t)=\sqrt{(x_0(t)-x(t))^2+(y_0(t)-y(t))^2}=cons.$ and centre in the actual ship position $\{x(t),y(t)\}$. The first coefficient $\psi_o(t)$, of the reference signal $r(t)$ is defined as the angle between the line passing through two points $\{x(t),y(t)\}$, $\{x_0(t),y_0(t)\}$ and the X_0-axis, see Fig. 3.

6. State feedback system for the linearised ship model

We take under consideration the ship model given by equations (1). From equations (1) we can find the relation between δ and ψ as a following transfer function

$$\frac{\psi(s)}{\delta(s)}=\frac{-0.005s^3-0.0003s^2-0.0001s}{s^5+0.2585s^4+0.0274s^3+0.0059s^2-0.0001s} \quad (20)$$

The relation between δ and p is given by formula

$$\frac{p(s)}{\delta(s)}=\frac{-0.0043s^4+0.0026s^3+0.0003s^2}{s^5+0.2585s^4+0.0274s^3+0.0059s^2-0.0001s} \quad (21)$$

We introduce the auxiliary variable u by formula

$$\frac{u(s)}{\delta(s)}=\frac{1}{s^5+0.2585s^4+0.0274s^3+0.0059s^2-0.0001s} \quad (22)$$

The state variables of the operation P (compare formulae (5), (20), (22)) can be defined in the following way

$$x_0(t)=u(t),\ x_1(t)=u'(t),\ x_2(t)=u''(t), \quad (23)$$

$$u''(t)=-0.06u'(t)-0.02u(t)-200\psi(t) \quad (24)$$

Based on the Theorem 2 and Theorem 3 we can conclude that system shown in Fig. 2 controls the considered ship model (1) or (2) with *ε-accuracy* to the reference signals from class $X\{W\}=L^2\{P\}$ (or $X\{W\}=M\{P\}$). To the class of a reference signals $L^2\{P\}$ belong all signals from space L^2, with bounded (in the sense norm of L^2 space) the first five derivatives.

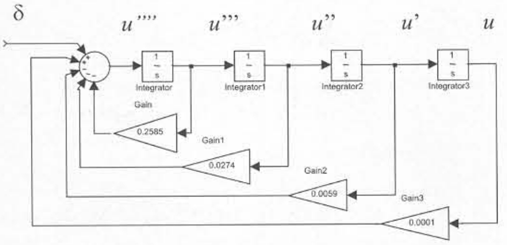

Fig. 4. Generator the state variables $u(t)$, $u'(t)$, $u''(t)$, $u'''(t)$, $u''''(t)$ of the operation P
Rys. 4. Generator zmiennych stanu: $u(t)$, $u'(t)$, $u''(t)$, $u'''(t)$, $u''''(t)$

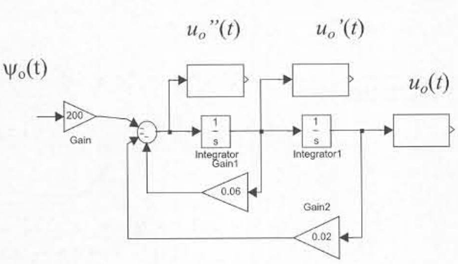

Fig. 5. Generator of the reference signal $u_0(t)$
Rys. 5. Generator sygnału zadanego $u_0(t)$

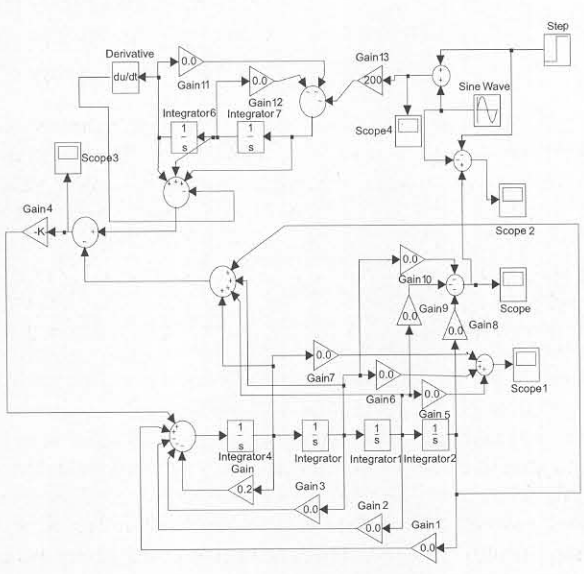

Fig. 6. Full scheme of the system controlling considered ship model
Rys. 6. Pełny schemat układu sterującego rozważanym modelem statku

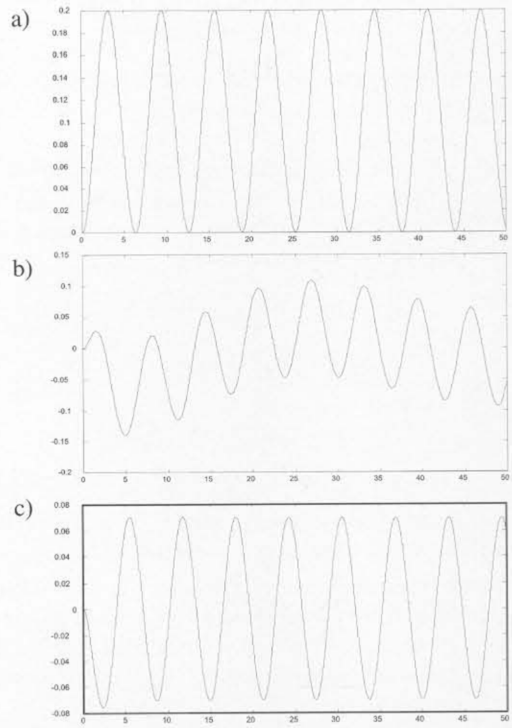

Fig. 7. Results of the simulations: a) Reference signal $\psi_0(t)=-0.1cos(t)+0.1$, b) Signal $p(t)$, c) Signal $\psi_0(t)-\psi(t)$
Rys. 7. Wyniki symulacji: a) sygnał zadany $\psi_0(t)=-0.1cos(t)+0.1$, b) sygnał $p(t)$, c) sygnał $\psi_0(t)-\psi(t)$

Based on the formulas (20)-(24) in prepared MATLAB SIMULINK simulations the classical analog model of the plant P and generator of the reference signal $u_0(t)$ has been used. The scheme of such systems is shown in Fig. 4 and Fig. 5. The full scheme of system controlling a ship model is show in Fig. 6. The exemplary simulations have been made for the feedback gain k=1000 and reference signal $\psi_0(t)=-0.1cos(t)+0.1$. Results of such simulations are shown in Fig. 7.

7. Conclusions

Presented above results of simulations confirm a high quality of the presented above control system. It should be noticed that considered state feedback control system is not sensitive for large changes of the parameters of the transfer function (20) denominator.

The presented in the paper method used for the linear systems can be extended to the non-linear cases (in the way similar as in the paper [5]). The Matlab-Simulink simulations was made for the non-linear ship motion model given by Blanke and Jansen [1]. This simulations also confirm the high precision control of this non-linear model by the system shown in Fig. 2.

References

[1] M. Blanke, G. Jensen: Dynamic properties of a container vessel with low metacentric height, Trans. Inst. MC. Vol. 19, No. 2, 1997

[2] L. M. Graves: Implicit functions and differential equations in general analysis, Trans. Amer. Math. Soc. 29, p. 514-522, 1927

[3] A. Lozowicki: Feedback systems realizing the inversion of some classes of operations, Archiwum Automatyki i Telemechaniki, Vol. XXIII, No. 4, p. 461-470 PWN, Warszawa, 1978

[4] A. Lozowicki: Use of a method of the operation inversion in control systems, Archiwum Automatyki i Telemechaniki, Vol. XXVI, No. 1, p. 91-106 PWN, Warszawa, 1981

[5] A. J. van der Schaft: L_2- gain and passivity techniques in nonlinear control, Lecture Notes in Control and Information Sciences, Springer, London, 1996

Tytuł: Wysokiej precyzji odporny układ regulacji ze sprzężeniem zwrotnym sterujący ruchem statku po zadanej trajektorii

Artykuł recenzowany