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# THE SYNTHESIS OF ROBUST FEEDBACK FOR DIAGNOSTIC OBSERVERS OF NAVIGATION SENSORS OF AUTONOMUS UNDERWATER VEHICLE

**FILARETOV, V[ladimir] F[edorovich]; ZHIRABOK, A[lexey] N[il] & ZUEV, A[lexander]**

***Abstract:*** *In this paper, the synthesis method of the robust feedback for the diagnostic observers of navigation sensors of the autonomous underwater vehicle (AUV) is proposed and studied. These diagnostic observers with proposed feedbacks allow to eliminate the influence of external disturbance and inexact knowledge of model parameters of the real AUV on the diagnosing process. The results of modelling have completely confirmed efficiency and high quality of the offered observers with feedback developed on its basis in various operating modes AUV.*
***Key words:*** *diagnostic system, navigation sensors, observer, robust, feedback, autonomous underwater vehicle*

## 1. INTRODUCTION

The autonomous underwater vehicles are complex technical systems which safety and reliable operation deserves particular attention. The navigation's sensors are one of the most important components of the AUVs which are necessary to control a motion trajectory at performance of autonomous underwater missions. There are some different methods of fault diagnosis: signal-based, analytical model-based, knowledge based (Alessandri, 1999; Jang, 2006).

In this paper, the method based on analytical model is used to provide the diagnosis process. In this case, the actual measurements of navigation sensors of AUV's are compared with a fault-free observer output signals driven by the control signals and measurements of other sensors. Difference between the actual sensor measurements and corresponding observer output signal is a residual signal which carries the information about the faults in the system. Diagnosis based on analysis of all residuals values. However, the parameters of AUVs model are known not precisely, therefore synthesized observers not always possess stability.

There are several approaches to robust diagnosing of AUVs subsystems (Amann, 1999). Their advantage is relative simplicity of the realization, however thus synthesized observers are capable to detect faults effectively only at horizontal movement of the AUV with low speed.

In this paper, to eliminate influence of external disturbance and inexact knowledge of model parameters of the real AUV on diagnosing process the new method of synthesis of robust feedback for diagnostic observers of navigation sensors of is proposed and investigated.

## 2. AUV DYNAMICS

The AUV dynamic behavior can be described by several sets of nonlinear differential equations. The AUV precise mathematical models are very complex, and they are simplified in practice. Assuming that the AUV motion is not controlled by the roll, and changes of the trajectory angles values are very small, the equations describing the movements of AUV in semi-associated system of coordinates have the following appearance (Ageev, 2000):

$$
\begin{aligned}
m_x\dot{v} &= -R_x(v,\alpha) + P\sin\vartheta + T_{x1}\cos\alpha\cos\beta - \\
&\quad -T_{y1}\sin\alpha\cos\beta - T_{z1}\cos\alpha\sin\beta, \\
m_y v\dot{\vartheta} &= R_y(v,\alpha,\dot{\psi}) + P\cos\vartheta + T_{y1}\cos\alpha - T_{x1}\sin\alpha, \\
J_{z1}\ddot{\psi} &= M_0\sin\psi + M_z(v,\alpha,\dot{\psi}) + M_{z\,ctrl}, \\
\dot{H} &= v\sin\vartheta, \\
m_z v\dot{\chi} &= R_z(v,\beta,\dot{\varphi}) + T_{z1}\cos\beta - T_{x1}\sin\beta, \\
J_{y1}\ddot{\varphi} &= M_y(v,\beta,\dot{\varphi}) + M_{y\,ctrl}.
\end{aligned}
\tag{1}
$$

Here $\varphi$ is a heading angle; $\theta$ is a roll's angle; $\psi$ is a pitch's angle; $\alpha$ is a attack's angle; $\beta$ is a drift's angle; $\chi$, $\vartheta$ are trajectory angles; $R_x$, $R_y$, $R_z$, $M_y$, and $M_z$ are the hydrodynamic forces and moments; $M_0$ is the specific stability moment; $m_x$, $m_y$, $m_z$, $J_{y1}$, and $J_{z1}$ are the masses and inertial moments of the vehicle with taken into account the water additional masses; $T_{x1}$, $T_{y1}$, and $T_{z1}$ are the components of the screws summary force; $M_{y\,ctrl}$ and $M_{z\,ctrl}$ are the control moments; $v$ is the velocity of the vehicle; $P$ is the remaining floating of the AUV; $H$ is the submergence depth; $V$ is the vehicle cubic capacity; $r_{0x}$, $r_{1x}$, $r_{2x}$, $r_{2y}$, $r_{2z}$, $C_y^{\omega}$, $C_z^{\omega}$, $\widetilde{m}_y$, $\widetilde{m}_z$, $m_y^{\omega}$, $m_z^{\omega}$ are the specific coefficients.

The AUV contains the following navigation-piloting sensors: the meter of pitch (variable $\psi$), the meter of heading (variable $\varphi$), the meters of pitch rate (variable $\dot{\psi}$) and heading rate (variable $\dot{\varphi}$), the meter of velocity (variable $v$), the meter of depth (variable $H$ ).

There are some different causes leading to these sensors fault. The faulty sensor should be early detected and isolated by the diagnostic system to avoid the erroneous mission fulfillment or loss of the AUV. Since the faults in the navigation sensors are incipient mainly, the detection of such kind of faults is of particular importance.

## 3. SYNTHESIS OF THE ROBUST FEEDBACK

The synthesized observers based on model (1) not always possess stability because the parameters of AUVs model are known not precisely. To eliminate influence of external disturbance and inexact knowledge parameters it is necessary to introduce the special feedback in observers.

Let's consider the model of diagnosed system (1) in a general form. This model will have the following appearance:

$$
\begin{aligned}
\dot{x}(t) &= F\big(x(t), u(t)\big), \\
y(t) &= Hx(t),
\end{aligned}
\tag{2}
$$

where $x \in X \subset R^n$, $u \in U \subset R^m$, $y \in Y \subset R^l$ are state vector, vector of control and vector of output accordingly; $F$, $G$ and $H$ are matrixes of the corresponding sizes.

In a general form, the observers captured by the robust feedback are described by the following system of the equations

$$
\begin{aligned}
\dot{x}_*(t) &= F_*(x_*(t), y(t), u(t)) + Kr, \\
y_*(t) &= H_* x_*(t),
\end{aligned}
\tag{3}
$$

where $K$ is a matrix of coefficients of strengthening of feedback.

Observers (3) generates the following residual:

$$r(t) = Ry(t) - y_*(t).$$

With taking it into account, and also that equality $RH = H_*\Phi$ (Filaretov, 2008) is true we can receive the following equation

$$r = RHx(t) - H_*x_*(t) = H_*(\Phi x - x_*) = H_*e,$$

where $e = \Phi x - x_*$ is residual of state vector, $R$, $\Phi$ are a some matrix.

Let's differentiate the equation for $e$:

$$\dot{e} = \Phi\dot{x} - \dot{x}_* = \Phi F(x,u) - F_*(x_*,y,u) - Kr, \quad (4)$$

where functions $F$ and $F_*$ are describe the dynamic of diagnosed system and observer.

Taking into account that $\Phi F(x,u) = F_*(\Phi x, y, u)$ we can rewrite equation (4) as:

$$\dot{e} = F_*(\Phi x, y, u) - F_*(x_*, y, u) - Kr = \quad (5)$$
$$= F_*(x_* + e, y, u) - F_*(x_*, y, u) - Kr.$$

We can see, that the component $F_*(x_* + e, y, u) - F_*(x_*, y, u)$ in equation (5) presents by self the derivate:

$$F_*(x_* + e, y, u) - F_*(x_*, y, u) = (\partial F_*/\partial x_*)e.$$

Taking this into account we can rewrite (5) as

$$\dot{e} = (\partial F_*/\partial x_*)e - KH_*e = ((\partial F_*/\partial x_*) - KH)e.$$

The derivative $\partial F_*/\partial x_*$ will have the next form for all six observers of navigation sensors of AUV:

$$\frac{\partial F_*}{\partial x_*} = \begin{pmatrix} 0 & \partial F_{*1}^{(j)}/\partial x_{*1}^{j} \\ 0 & \partial F_{*2}^{(j)}/\partial x_{*2}^{j} \end{pmatrix},$$

where $j$ is a number of observers $j$=1,..,6.

As $H_{*l}^{(j)} = (1 \quad 0)$ and vector have next form $K_{*l}^{(j)} = \begin{pmatrix} K_{*1}^{(j)} & K_{*2}^{(j)} \end{pmatrix}$ then we can receive the following equation

$$\dot{e} = \begin{pmatrix} -K_{*1}^{(j)} & \partial F_{*1}^{(j)}/\partial x_2^{j} \\ -K_{*2}^{(j)} & \partial F_{*2}^{(j)}/\partial x_2^{j} \end{pmatrix} e.$$

Solving the given equation we will obtain the coefficients of matrix $K_{*l}^{(j)}$ for each observer:

$$K_{*1}^{(j)} = \partial F_{*2}^{(j)}/\partial x_2^{j} - (\lambda_1 + \lambda_2),$$
$$K_{*2}^{(j)} = 1/\left(\partial F_{*1}^{(j)}/\partial x_2^{j}\right) - \quad (6)$$
$$-\left(\lambda_1\lambda_2 + \left(\partial F_{*2}^{(j)}/\partial x_2^{j}\right)^2 - \left(\partial F_{*2}^{(j)}/\partial x_2^{j}\right)(\lambda_1 + \lambda_2)\right),$$

where $\lambda_1 = \lambda_2 = -1$.

Thus, on the basis of (6) and taking into elements of matrix $\partial F_*/\partial x_*$, the feedback for each observer are developed. This provide the robustness for diagnosis system.

## 4. RESULTS OF SIMULATION

The numerical simulation of the synthesized observers closed by feedback (6) was carried out for verification of the received results. At simulation the paparemetrs of real autonomous underwater vehicle were used [Ageev, 2000].

Defects in sensors are simulated by linearly increasing change of the signals which action begins at the moment of time $t$=30 and stops at $t$=70. Modeling is spent at zero initial conditions AUV and observers. At simulation change of the attached weights, hydrodynamic forces and the moments was set.

The simulation showed that at the presence of the some external disturbance and inexact knowledge parameters of model the simple observers without feedback have not provide the stability (see Fig. 1.). Therefore it can lead to erroneous decisions in the course of exploitation of AUVs. Estimations of errors of other sensors formed by observers with feedback are characterized by similar behaviour. It's possible to see (see Fig. 2) that observers with feedback for diagnosing of navigation-piloting sensors of autonomous underwater vehicles completely has confirmed the working capacity and high quality.

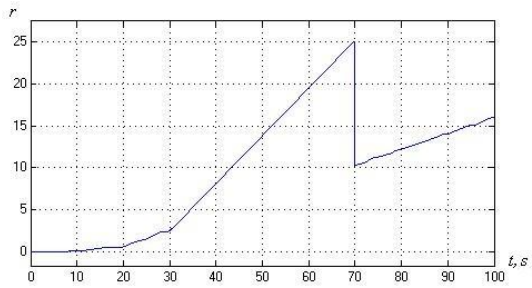


Fig. 1. An estimation of an error of pitch rate sensor

The estimation of an error of pitch rate sensor, formed on the basis of the observer captured by feedback (6) is presented on Fig. 2.

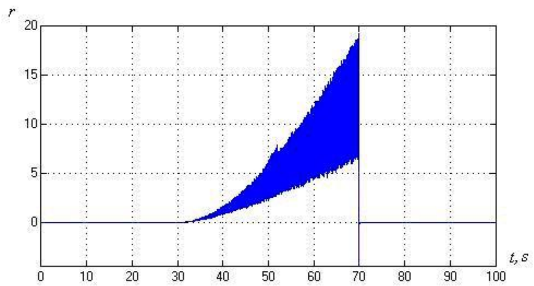


Fig. 2. An estimation of an error of pitch rate sensor on the basis of observers with feedback

## 5. CONCLUSION

This paper deals with the problem of development of the robust feedback for observers of navigation sensors of autonomous underwater vehicles. Proposed diagnostic observers with robust feedback allow eliminating the influence of external disturbance and inexact knowledge of model parameters of the real AUV on diagnosing process. Results of modelling have completely confirmed efficiency and high quality of the offered method and the observers with feedback developed on its basis in various operating modes AUV.

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