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Ship's course stabilization accuracy improvement by implementing dual-loop control system

Ya Volyanskaya[1], S Volyanskiy[1], O Onishchenko[2], V Shevchenko[2]

[1]Admiral Makarov National University of Shipbuilding, Heroiv Ukrainy ave., 9, Mykolayiv, Ukraine, 54000
[2]National University "Odesa Maritime Academy", Didrihsona str., 8, Odesa, Ukraine, 65029

E-mail: yanavolyanskaya@gmail.com

Abstract. This study addresses the problem of ship's course stabilization accuracy improvement in order to reduce trip distance and fuel consumption. The method is to upgrade autopilot control diagram. Proposed block diagram of a dual-loop control system allows to estimate the effects of disturbances and form the positive feedback transfer function. Dual-loop course control system Matlab/Simulink model was developed in the paper. Mathematical modelling analysis shown the effectiveness of such system in course accuracy improvement by compensating of wind-wave disturbances. In addition, proposed system operation modelling analysis demonstrated ship's course keeping system response time improvement with the use of estimated disturbance positive feedback loop.

1. Introduction

Ship's navigation safety and operational characteristics improvement are important tasks of modern maritime transport. Such tasks require continuous development of ships' navigation control systems. One of the key components of a ship's navigation control system is the course control system (autopilot).

The course control system of a modern marine ship must comply with international requirements (IMO Res. A.342 (IX), IMO Res. MSC. 64 (67) Annex 3, IMO Res. A694 (17), IMO Res. A.822 (19) and ISO11674 (2006) / 16329 (2003) for High Speed Crafts, IEC 62065 Track Control System).

According to the requirements the main tasks of the autopilot are: automatic course keeping, course changing with set angular velocity or given radius, ship's track control using Electronic Chart Display and Information System (ECDIS).

Autopilot effective operation leading to reducing ship's yawing and, as follows, reduces propulsion energy loses and fuel consumption. Thus, the development of autopilots and track control systems which provides accurate course changing and stabilization in varying weather and load condition is an important task.

The goal of this research is ship's course stabilization accuracy improvement by upgrading an autopilot configuration in order to take into account wind-wave disturbances.

2. Research findings

Today most of automated course control systems (ACCS) operation is based on the use of a ship's mathematical model [1–5]. Obviously if ship's dynamics mathematical model (MM) is more accurate then it's allows to synthesize ACCS more effective and as follows to decrease loses, steering gear load and fuel consumption for propulsion.

At present, ship's movement control theory allows to use different MM [3, 4] which describes adequately ship's movement physical processes. Usually marine ship mathematical model is based on six degrees of freedom rigid body movement mathematical model [2, 4, 5]. International Maritime Organization (IMO) had developed and adopted resolution A.751(18), regulating the necessity of ship's dynamics MM use when solving navigational safety practical tasks [6]. Simplified Nomoto-

models [1–3, 6, 7] are recommended by authorities to use in marine autopilots. Second order Nomoto model [4, 6–8] can be described by equation:

$$T_1 \cdot T_2(d^2\omega/ dt^2)+(T_1 + T_2)(d\omega/ dt)+\omega+H(\omega)= K \cdot \alpha_r + KT_3(d\alpha_r / dt), \qquad (1)$$

where ω – angular velocity (speed) of the ship; $H(\omega) = \nu_1|\omega|\omega + \nu_2\omega^3$ – the nonlinear function of the angular velocity; $T_1, T_2, T_3, K, \nu_1, \nu_2$ – the parameters of the mathematical model; α_r – rudder angle.

Equation (1) parameters estimation are presented in [9], where is taken into account that $d\psi(t)/dt =K_1\cdot\omega(t)$. In this formula are indicated: $\psi(t)$ –course angle; K_1 –ship design factor.

Modern autopilots configuration (*NAVPilot* xxx *Series* from *Furuno*, *AP3xxx* from *Navis Engineering OY*, *PT500D* from *Yokogawa*, *NautoPilot* 5000, *NP2025PLUS* from *Raytheon*, *PilotStar D*, *Saura SA-10*, *Navitron*, etc.) allows to adjust its operation modes flexibly, taking into account various factors and external influence, using various sensors. As example it is shown on Fig. 1 "*NAVIPILOT* 4000" autopilot block diagram.
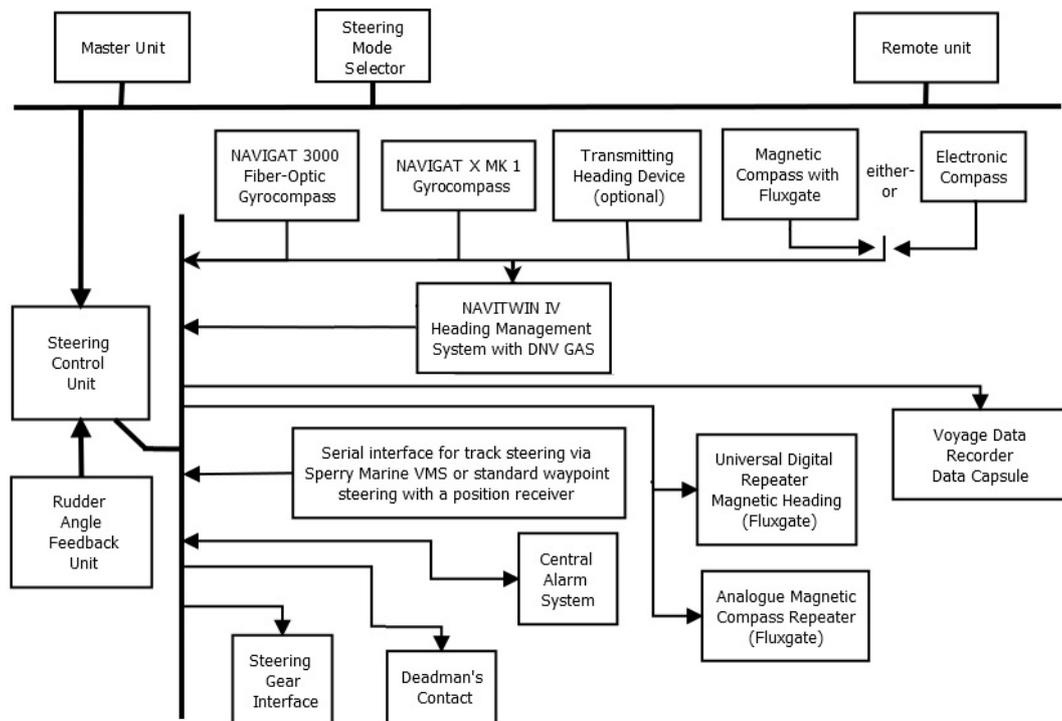
Figure 1. Block diagram of the "*NAVIPILOT* 4000" autopilot

Most well-known ACCS [1–4, 10–13] use the PID-regulation algorithms and are based on the stabilization principle "by deviation". But there is a class of control systems based on the principles of dual-loop (combined) control. However, this principle is almost not applied in the ACCS due to the difficulty of external disturbances measurement.

The most sufficient external load (wind, wave) acting on the ship is complex and forms the main disturbing effect on the course stabilization system (CSS). Preliminary, in general form, we will consider the CSS operation features based on the application of two-loop control principle.

Let's assume that main disturbance $I(s)$ at any point of time and its application point to controllable parameter $Y(s)$ stabilization system are known. By adding to any stabilization system disturbance invariance properties it is possible to improve system's static and dynamic properties without losing its stability [7, 8]. One of the requirements of the invariance theory is the presence of two disturbance measurement loops. Thus the main tasks are disturbance measurement, processing and inputting

(second loop) in stabilization system. But in control systems practical implementation it is impossible to achieve absolute invariance. It should be noted that real two loop control systems, as a rule, are providing the compensation of just one chosen disturbance.

Let the perturbation $I(s)$ act on the control object $W_o(s)$ in a closed system ($X(s)$ – is the master signal of the system, $Y(s)$ – is the initial coordinate). The system contains elements described by transfer functions: $W_p(s)$ – PID-regulator, $W_o(s)$ – control object, $W_{fb}(s)$ – feedback sensor. In cases where it is possible to provide additional loop with disturbance information, turning $+ I(s)$ into $- I(s)$ the influence of this disturbance can be completely compensated, as follows from the expression:

$$W(s) = \frac{Y(s)}{X(s)} = \frac{X(s) \cdot W_p(s) \cdot W_o(s) - I(s) \cdot W_o(s) + I(s) \cdot W_c(s) \cdot W_p(s) \cdot W_o(s)}{1 + W_p(s) \cdot W_o(s) \cdot W_{fb}(s)}, \tag{2}$$

if for (2) the condition $I(s) \cdot W_o(s) = I(s) \cdot W_c(s) \cdot W_p(s) \cdot W_o(s)$ is set, then the formal condition for complete invariance to $I(s)$ is $W_c(s) = 1/W_p(s)$.

For the operation of additional loop, it is necessary to provide a disturbance sensor $I(s)$ and physically implement the transfer function (TF) of the compensator $W_c(s)$, which is the reverse TF to the regulator $W_c(s) = 1/W_p(s)$. This will allow us to obtain the value of the disturbance $I(s)$ with a minus sign.

If the transfer coefficients of the measurement node $I(s)$ and compensation $W_c(s)$ remain unchanged over a wide range of amplitudes and frequencies, then the invariance property of the control system will exist for almost all amplitudes and frequencies of disturbance $I(s)$.

However, practical implementation of disturbance compensating input signal, for the real CSS, is quite difficult. It is connected with the technical difficulties of wind-wave disturbances direct measurement.

In this article is proposed a simple method of adding the wind-wave disturbances partial invariance to the ACCS, based on the indirect determination of the basic disturbance $I_c(s)$, which causes ship's course deviation. Indirect measurement of the main disturbance is based on the principle shown on Fig. 2 – the desired disturbance I_c will be determined basing on measurements of the signals X_1 and Y_1, i.e. $I_c = X_1 \cdot W_1(s) - Y_1/W_2(s)$.
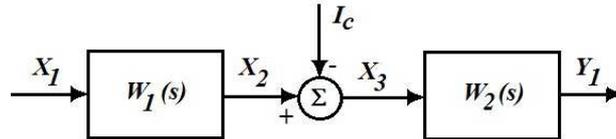
Figure 2. The principle of indirect disturbance measurement

As indicated above, to implement a two-loop control system, it is necessary to know the disturbance application point. It is assumed that the main disturbance $I_c(s)$ can be matched to the rudder angle what is acceptable from automation theory point of view. Dual-loop CSS functional diagram is presented on Fig. 3.
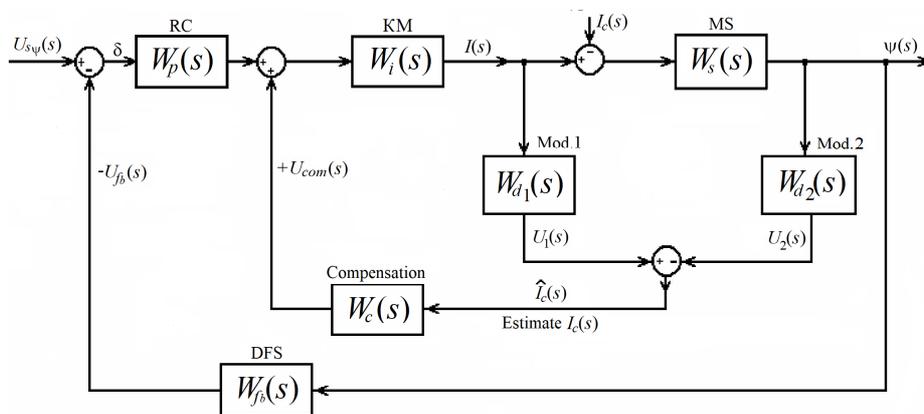
Figure 3. The functional diagram of a dual-loop CSS providing partial invariance to $I_c(t)$

In Fig. 3 marked: RC – ship's course ψ regulator; KM – steering gear control closed loop; MS – Nomoto second order model transfer function; DFS – feedback sensor (course angle) Mod. 1, Mod. 2, Compensation – accordingly, the device for measuring and inputting a compensating disturbance positive feedback in the CSS.

The main disturbance can be estimated by expression, which follows from the diagram shown in Fig. 2:

$$I_c(s) = I(s) - \psi(s)/W_s(s) \tag{3}$$

accordingly $\hat{I}_c(s) = U_1(s) - U_2(s)$, and $\hat{I}_c(s) \approx I_c(s)$, and where $W_s(s)$ is the transfer function of the ship's model.

Obviously, the digital or analog implementation of expression (3) requires the calculation of derivatives with all known technical problems and limitations. Note that rudder angle and course angle ψ real measurement devices have filtering properties and often can be described by aperiodic link with the time constants T_c and T_{T}, respectively. Let's install a filter with a transfer coefficient and a time constant at the output of the steering angle sensor, exactly the same as that of a course angle sensor, and a filter with a transfer ratio and time constant, like that of a steering angle sensor at the output of the course angle sensor. This simplifies the technical implementation of the system by obtaining a common denominator in the transfer functions. Taking into account the above, the structural diagram part, which allows to estimate the main disturbance $I_c(s)$, is shown in Fig. 4.

It should be noted that the estimated value of the main disturbance will always have a dynamic error, which in the best case is determined by the inertia of the second-order aperiodic link $1/((T_c \cdot T_{\text{T}}) \cdot s^2 + (T_c + T_{\text{T}}) \cdot s + 1)$.

The disturbance, which is estimated with the use of the structural diagram shown in Fig. 4, is determined by the expression:

$$\hat{I}_c(s) = I_c(s) \cdot \frac{K_{\text{T}}}{(T_{\text{T}} \cdot s + 1)} \cdot \frac{K_c}{(T_c \cdot s + 1)} \cdot \tag{4}$$

The expression (4) includes the component $1/W_s(s)$, according to (3).
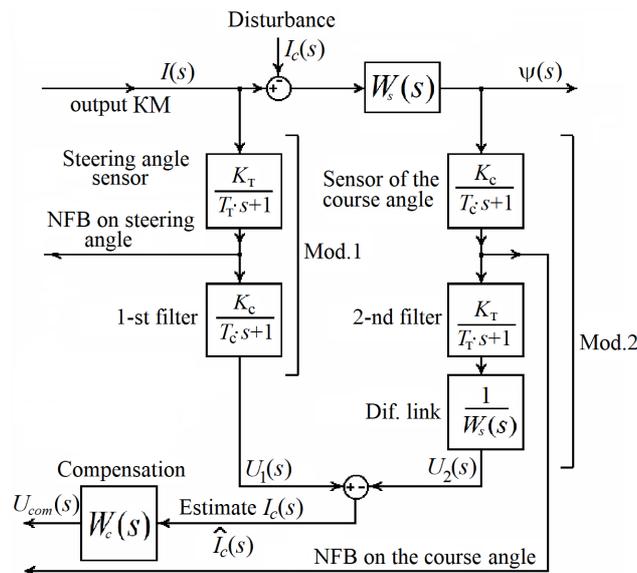
Figure 4. The section of the structural diagram (see Fig. 2), providing estimation of the main disturbance

It's obvious that:

- the $\hat{I}_c(s)$ estimation resulting accuracy depends on the accuracy of the technical implementation of the expression $1/W_s(s)$;

- in a system with a course angle sensor and an observation, the estimation will be rough, since the inertia of such a measuring channel is quite high and comparable with the inertia of the steering gear;

- the compensating link transfer function $W_c(s) = W_i^{-1}(s)$ cannot be precisely implemented, since

$$W_i(s) \approx \frac{1/k_{\text{T}}}{2 \cdot T_{\mu1}^2 \cdot s^2 + 2 \cdot T_{\mu1} \cdot s + 1}.$$

Therefore, we accept

$$W_c(s) = \frac{2 \cdot T_{\mu1} \cdot s + 1}{0{,}05 \cdot T_{\mu1} \cdot s + 1} \cdot k_{\text{T}}, \tag{5}$$

which, in turn, is also simplified based on an approximate mathematical model of the ship's steering gear.

A ship's mathematical model based on expression (1) can be presented in MatLab/Simulink application (Fig. 5). This model includes non-linearity $H(\omega) = \nu_1 |\omega|\omega + \nu_2\omega^3$ with the use of blocks: Product, Gain 2, Gain 5, Gain 6, Add and Abs.
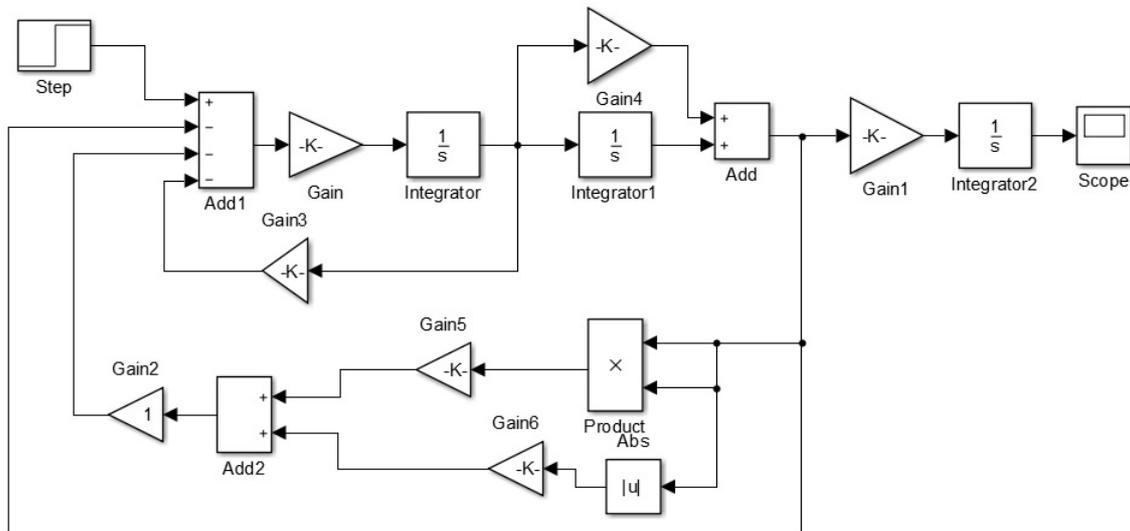
Figure 5. The implementation of the expression (1) in MatLab/Simulink (Subsystem i Subsystem 4, shown in Fig. 6)

Fig. 3 system modeling, was carried out using the scheme created in MatLab/Simulink (see Fig. 6), using the methodology described in [17–20]. The main disturbance was modeled as a periodic sum of two harmonic effects (SineWave) of different amplitude, frequency and phase shift.

For simulation was used the icebreaker vessel model with the length of the vessel at the design waterline L_{wl} = 70,5 m, volumetric displacement W = 2864 m^3, the total power of the SPP N = 4600 kW, with the ship speed interval V = 2 ... 20 kn. The parameters of model (2) are based on the results of identification [6, 7, 9, 16] (see Table 1.)

Table 1. Identified parameters

K	ν_1	ν_2	T_1	T_2	T_3
0,031	$-1{,}7 \cdot 10^{-3}$	$-6{,}1 \cdot 10^{-4}$	31	15	5

Figure 6. Ship's ACCS model with the implementation of the principle of two-loop control based on the indirect determination of the main disturbance

The steering gear dynamics is described by the aperiodic TF with time constant $T_i = 3,5$ s.

Fig. 7 shows the resulting disturbance (graph 1). This disturbance causes a significant change in the ship's course. Autopilot is compensating this disturbance using the PID controller. The parameters of the PID controller are selected using the synthesis of a closed system and are almost optimal for chosen conditions.

Analyzing the simulation results, can be concluded that the stabilization of the course angle ψ at a given CSS value of $-5°$ with a deviation of $\pm 2°$ (graph 2) with the conventional system with a PID controller is not sufficient.

Figure 7. Results of system modeling (see Fig. 2 and Fig. 3), taking into account the effect of the main disturbance compensation

Using the proposed estimation $I_c(t)$ and adding the additional compensation loop for the resulting disturbance (see Fig. 3 and Fig. 4), the dynamics of the system, even without changing the autopilot PID controller setting, was significantly improved. This is illustrated in graph 3 shown in Fig. 7, which

shows the estimated value of $I_c(t)$ (almost coincides with graph 1). Graph 4 – shows the change in the course angle in the proposed course stabilization system, which is partially invariant to disturbances.

3. Conclusions

Dual-loop ship's course control system simulation analysis shows that offered approach to the course stabilization accuracy is effective and allows sufficiently improve quality of course control. As can be seen from simulation results, resulting disturbance compensation, using the classical stabilization system "on deviation" and PID autopilot controller, the maximum dynamic course deviation is ± 2°. Under similar weather conditions, but using the proposed dual-loop system, which is partially invariant to disturbances, we obtain a maximum dynamic deviation close to 0,35°.

In addition, proposed system operation modelling analysis demonstrated ship's course keeping system response time improvement with the use of estimated disturbance positive feedback loop. This improvement will lead to fuel consumption reduction and saving of steering gear service life. Of course, the proposed system requires further experimental studies.

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